中国光储直柔建筑发展战略路径研究

（二期）

Research on the Strategic Path of PEDF Buildings in China (Phase II)

子课题 3：农村“光储直柔”新型电力系统研究

Task 3: Research on the PEDF Power System in Rural Areas

清华大学

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执行摘要

1. 农村能源系统的困境与机遇

- **我国农村建筑能耗巨大。**我国农村地区用能约占全社会建筑能耗的四分之一，农村建筑用能包括 2.2 吨标准煤商品能的使用以及 0.9 亿吨的生物质直接燃烧。同时，农村是我国散煤使用率最高的地区，散煤的使用量约 1.1 亿吨标准煤。农村建筑运行碳排放约 4.2 亿吨，约占全国建筑碳排放的 20%。

- **我国农村用能造成了高昂的环境代价。**由于我国大部分农村主要采用燃烧化石能源的方式满足自身的用能需求，尤其是北方农村采暖。化石能源的燃烧不仅释放大量二氧化碳，还会造成严重的空气污染。化石能源的燃烧产物如 PM2.5、氮氧化物、一氧化碳等会严重危害室内人员的健康。根据世界卫生组织报告，2019 年中国有 103 万人死于空气污染，其中 62%发生在农村。

- **农村“煤改电，煤改气”方案的效果并不理想。**从 2017 年开始，我国开始实施“煤改电，煤改气”工程，但是由于缺乏合理的顶层设计，天然气和市政电力的价格过于昂贵，大部分地区的农户在补贴结束后又用回了散煤。因此，不能把在农村地区实现“碳中和”的任务简单地理解为一个能源替代工程，而是一个需要详细可靠的规划来引导的复杂方案，方案包括科学的技术创新、实际的工程应用、完备的政策引导。这需要在技术、政策、商业模式上进行全面的改革和创新。

- **农村能源革命与国家战略息息相关。**习近平主席在 2020 年的联合国大会发言中宣布中国“二氧化碳排放力争于 2030 年前达到峰值，努力争取 2060 年前实现碳中和”。国务院文件强调：脱贫攻坚目标达成后，我国“三农”工作重点向全面推进乡村振兴战略转移，农村能源转型是促进农村产业发展和农村生态治理的主要手段，更是实现乡村振兴战略的重要基础。建立农村新型能源系统是实现“碳中和”的必经之路！也是促进农村生态治理、乡村振兴的重要基石。

- **农村具有发展光伏系统的空间优势。**实现碳中和战略的主要任务之一是实现从以化石能源为基础的碳基电力系统转为以可再生能源为基础的零碳电力系统。因此，实现农村用能脱碳就要全面推动农户用能电气化，并利用可再生能源代替火电。而农村在发展可再生能源有得天独厚的空间优势。根据卫星图像识别的结果，我国农村屋顶面积丰富(130 亿㎡)，

可安装 19 亿 kW 光伏，光伏年发电量可达 2.5 万亿 kWh，是未来农村实现全面电气化后所需用电量的 3-4 倍。因此，在农村发展以分布式光伏为核心的新型电力系统可以充分利用农村巨大的光伏潜力，从而使得农村从一个传统的能源消费者转变为一个能源的生产者。

2. 中国农村要建立以屋顶光伏为基础的新型电力系统

- **传统的直接逆变上网的方式不能帮助农村实现能源转型。**目前农村的光伏系统的运行模式是：开发商租赁农户的屋顶安装光伏板，光伏发电直接逆变上网，而农户依然需要从电网取电满足自身的用电需求。这样的光伏系统存在三个问题：1，不公平：变压器的容量有限，每个村仅少数“捷足先登”的农户能享受上网容量。这种方式浪费了巨大的农村屋顶光伏潜力；2，不充分：这种系统的发电和用电是两个体系，开发商获得了卖电的收益，但是农民无法真正受益。而且，农民没有享受到光伏电力，这种光伏系统并不能改变农村原有的能源结构；3，不平衡：光伏发电具有随机性和波动性，直接入网容易产生垃圾电，无法利用农村储能资源，浪费大量调峰电源资源。因此，现有的光伏系统无法引领农村用能的脱碳化，农村需要一种新的可以让农民享受光伏电力、为农民带来真正实惠的电力系统。
- **农村光储直柔新型电力系统推动农村能源结构的变革。**为了克服传统的农村光伏系统所带来的不公平、不充分、不平衡的问题，光储直柔新型电力系统应运而生，它的基本原则是优先自发自用，余电有序上网。该系统的运行方式是：光伏电力优先满足农户的用电需求以及储电设备的充电需求，然后多余的电力响应电网的调度有序地送入电网。与传统的农村光伏系统相比，这样的系统有三个优势：1，变压器的扩容压力小，因为相当一部分比例的光伏电力被就地消纳了，就可以允许有更多的农户参与到这个系统中；2，充分利用农村的储能优势，使得光伏电力不再是垃圾电，不会增加电网的调度压力；3，农户直接使用光伏电力，不仅获得经济上的实惠，而且带动农村全面电气化以及农村用能脱碳化。

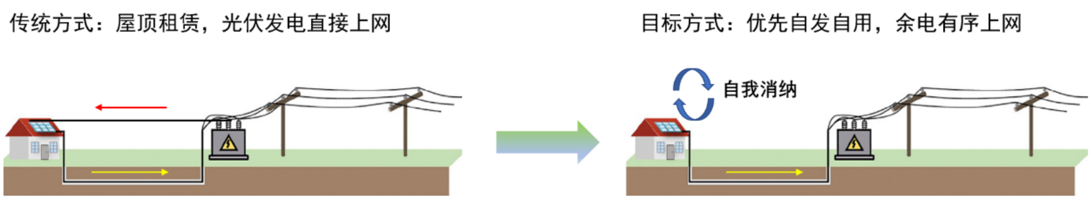

图 I 光储直柔系统与传统光伏电力系统的对比

3. 农村新型电力系统设计方案

- **农村新型电力系统的挑战是解决光伏电力与农户负荷的不匹配。**光伏电力与农户用电之间存在严重的不匹配，这是农村新型电力系统面临的最大的挑战。在逐时的时间尺度上可以看出，由于光伏发电特征与农户用电特征不一致，导致光伏电力无法始终满足农户的用电需求。而解决这个问题的关键，是控制策略和储能技术。储能可以实现光伏电力的转移，使得农户在夜间和阴雨天通过储能设备的电力就可以满足自身用电需求。而控制策略决定系统的运行规律，可以使得系统能够按照预期方案平稳运行。

- **新型电力系统的拓扑方案需要因地制宜。**确定系统拓扑结构是农村新型电力系统设计的基础。目前农村“光储直柔”电力系统的拓扑结构大致分为三种。不同的拓扑结构会导致不同的发电效率、传输损失、设备容量、控制方法以及投资费用。三种方案各有利弊，因此在实际项目中需要因地制宜，综合考虑当地的电价、设备成本、上网政策、柔性目标等进行经济性对比，从而选择性价比最高的方案。

- **新型电力系统的设备容量选择要兼顾可靠性和经济性。**选定电力系统设计方案的拓扑结构后，需要确定系统的设备容量，即：光伏装机容量、储电容量以及各种变流器的容量。理论上讲，光伏容量越大，发电收益越大；储电容量越大，系统的调控能力越强，柔性潜力也越大。但是在实际工程中，受到成本的限制，系统的设备选择是一个优化问题，兼顾系统运行可靠性以及经济性。系统设计容量需要满足两个约束条件：（1）多云天气一天内的光伏发电量不小于农户的用电量；（2）户内电池满足农户夜间以及阴雨天的用电需求。

- **新型电力系统需要去中心化的自适应控制方法。**由于农村建筑的特征是“量大面散”，传统的集中控制的方式难以适应农村的场景。对于直流系统，电压是最简单也是最重要的运行参数，可以利用电压信号作为控制信号来改变设备的运行状况。具体来说，就是系统中的电力电子设备感应接触点的电压信号，根据电压的高低来改变自己的运行状态。这是一种去中心化无控制器的控制方法，设备根据所在位置的电压信号做出自适应的调节，维持系统的稳定运行。

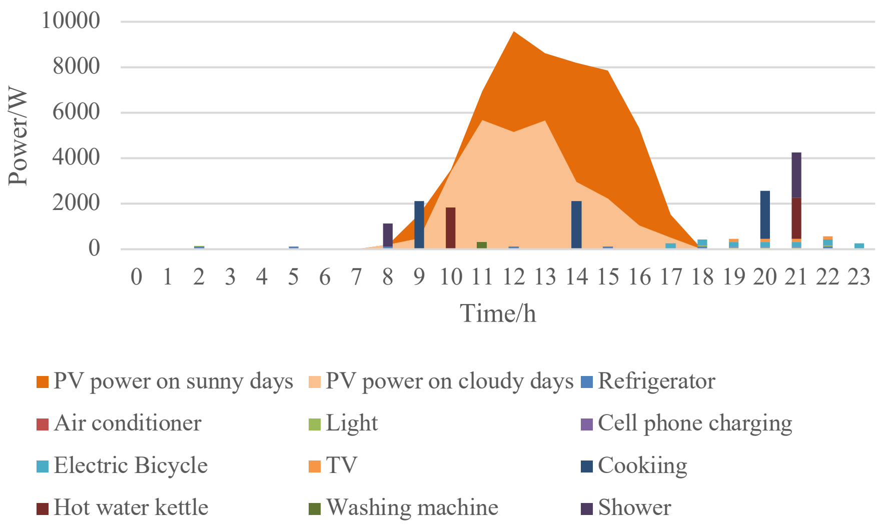

图 II 光伏电力与农户用能的逐时对比

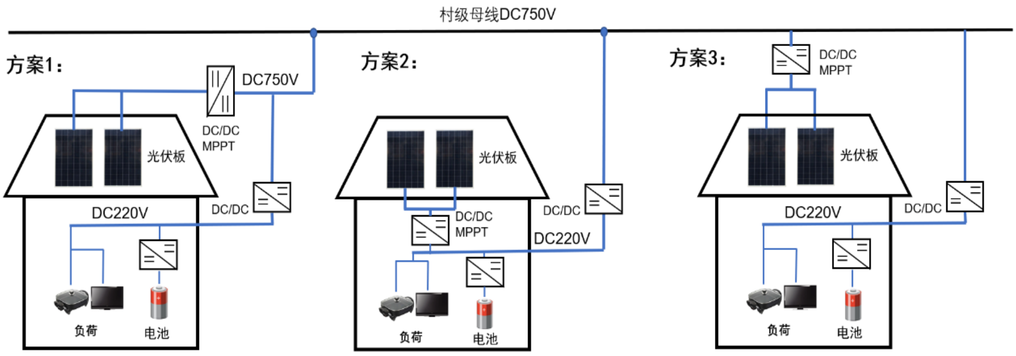

图 III 常见的农宅光伏拓扑结构

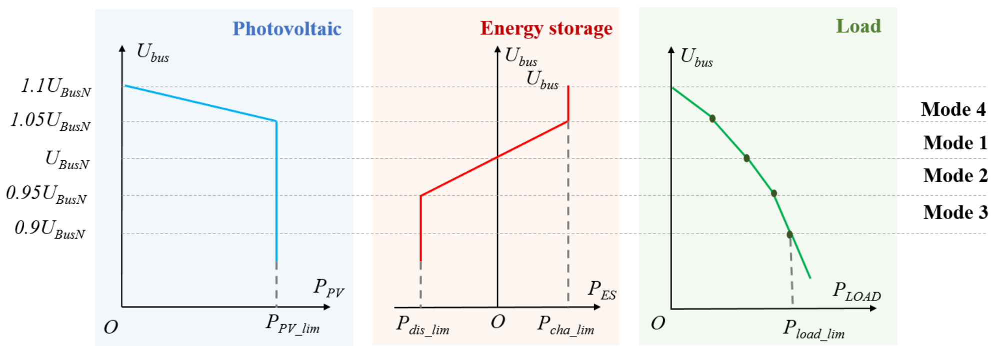

图 IV 基于母线电压控制原理

4. 农村光伏供暖方案要服务于房间的功能

- **对于全天使用的房间需要采用低成本的储能方案。**对于卧室这种全天使用的房间，热负荷稳定，任何时刻都需要供暖。然而光伏电力在夜间以及阴雨天难以满足房间的供暖需求。因此需要将晴天白天的发热量转

移到夜间以及阴雨天才能与房间热负荷相匹配，这样的热量转移过程可以通过储能的方式实现。但是储电的成本太高，农户难易承受。而传统的储热技术成本比较昂贵，占地空间大，难以在农宅中实施。因此，可以采用墙体进行储热的方式，红砖价格低廉，同时墙体占地面积小，基本不压缩农户的生活空间。供暖末端采用光伏直驱电热丝的方式，由于电热丝在运行的过程中不需要控制电压或者功率的稳定性，因此降低了控制设备的成本。经过测试，房间的冬季黑球平均温度为 16℃，满足农户的热舒适需求。

- **对于间歇使用的房间需要采用低成本的控制策略。**对于厨房、客厅这样间歇使用的房间，采用储热的方法反而会降低系统控制的灵活性，浪费储热资源。因此，采用光伏驱动热风机的方法对间歇使用的房间进行供暖，因为热风机系统的升温速度快，可以快速响应室内人员的变化，适合于间歇使用的房间。然而这样的系统需要克服光伏电力的波动性从而控制输出功率和电压的稳定，在新型电力系统中可以采用电压信号的控制方法。测试结果显示，在白天，热风机的电力几乎全部来自于光伏电力，而且系统在任何时刻保持输出功率满足热风机的用电需求。

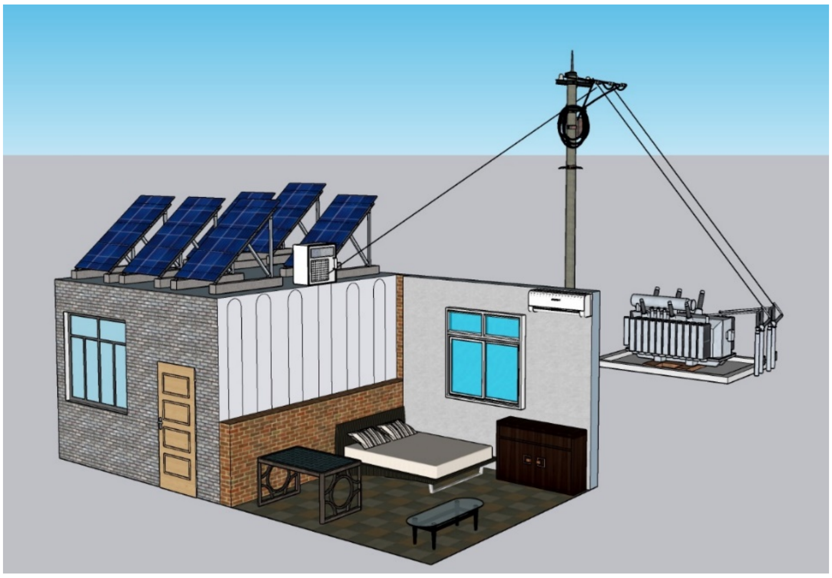

图 V 基于墙体储热的光伏供暖系统

5. 电动农机将为农村新型电力系统提供储能资源

- **农机电气化是未来农业机械发展的必然趋势。**随着农村全面电气化的推进，农业机械电气化将会成为农村潜在的储电资源，为农村新型电力系统提供调蓄作用。19 世纪 80 年代，世界上开始出现了电动拖拉机，距今为止，电动拖拉机已经过了 130 多年的发展，其发展历程可以大致

分为电网供电阶段与蓄电池供电阶段。进入 21 世纪后，随着能源危机的逐渐加深以及新能源技术的飞速发展，电动拖拉机也迎来了高速发展时期，主要特点如下：①集成先进的电力电子技术，进一步提高了电动拖拉机的轻便性和灵敏性；②增程式电驱技术的出现提高了电动拖拉机对大功率农田作业的适应性，促进了大功率电动拖拉机的发展；③电池技术的极大发展大幅提高了电动拖拉机的额定功率和续航时间。

- **中国农机电气化进程还在起步阶段。**我国电动拖拉机的研发起步较晚，直到 1960 年，哈尔滨松江拖拉机厂成功试制了我国首台电动拖拉机。之后进入发展的相对停滞阶段，到 2010 以后，中国的电动农机才迎来井喷式的发展。随着电动拖拉机动力电池、电驱动技术、整机及部件控制技术以及牵引性、动力性及经济性等拖拉机使用性能的改善，国内电动拖拉机的研发取得了很大进展，但电动拖拉机实际生产和应用范围非常有限，电动拖拉机在整机重量、续航时间以及额定功率等性能方面还有较大改善空间。

- **农机电气化提供丰富的储能资源。**通过调研不同传统农机的工作时长和功率范围，结合目前常用的磷酸铁锂电池的参数，对常用农机电气化的电池容量进行预测。拖拉机械的储能潜力范围最大，为 11 ~ 589kW·h，这是由于其作为动力装置的组合特性决定的。植保机械和耕种机械由于配套使用，整体的储能潜力相对较大，分别有 0.04 ~ 71 kW·h 和 8 ~ 14 kW·h 的储能潜力。运输机械的储能潜力为 6 ~ 165 kW·h。储能容量相对小的几类农机分别为的打药机、喷雾机、移栽机、牧草机、微耕机以及田园管理机。它们的储能潜力在 10 kW·h 以内，同时在农户家中较为常见，可基本满足户级新型电力系统的储能调度需求。

- **电动农机储能的方式能适应不同的农村场景。**对于目前农机户用使用模式，生产侧电动设备如割草机、喷雾机、微耕机等，可提供至少 9 kW·h 的储能潜力。交通侧电动设备如电动两轮车、电动三轮车和低速电动汽车等，该类设备可提供至少 9.5 kW·h 的储能潜力。因此，电动农机能为户级的农村新型能源系统提供至少 20 kW·h 的储能潜力，可满足农户的储能调度的需求。在未来土地规模化经营的场景下电动农机的情况，大型电动农机的种类将大幅增加，户用电动农机设备与规模化经营一方的电动农机设备将通过电池柜及拼装电池等方式进行有序的充分互动。

- **农机电气化将对农村的减碳做出巨大的贡献。**通过构建一个自上而下的模型对不同规划情景下农业机械的电气化带来碳减排收益进行预测。模型预测在 2025 年农业机械总动力为 113687.7 万千瓦。仅在市场推动

下，我国电动农机的渗透率发展较为缓慢，2040 年为 26.04%，实现 357.81 千吨 CO_2 的减排收益。在高速发展的情景下，在 2035 年，农业机械电动化带来 357.81 千吨 CO_2 减排收益，将是市场推动场景下的 5.83 倍。积极的政策引导来推广农机电气化可以带来十分可观的碳减排收益。

- **农机电气化的挑战是电池和电机技术。**农机电气化最大的技术难点是电池，电动农机功率大，对运行时长有要求，因此电池要满足容量大、比能量大的特征。同时农机工作时产生强烈的震动，对电池的安全性和散热性能的要求也很高。由于工作环境特殊，对电动机性能要求比较高。首先就是要能适应恶劣工作环境，防尘防水可靠性强；其次要有较大的调速范围满足不同工况；然后要能承受突变载荷，具有一倍以上过载能力；最后实际使用中具备高转矩和较高瞬时输出功率。

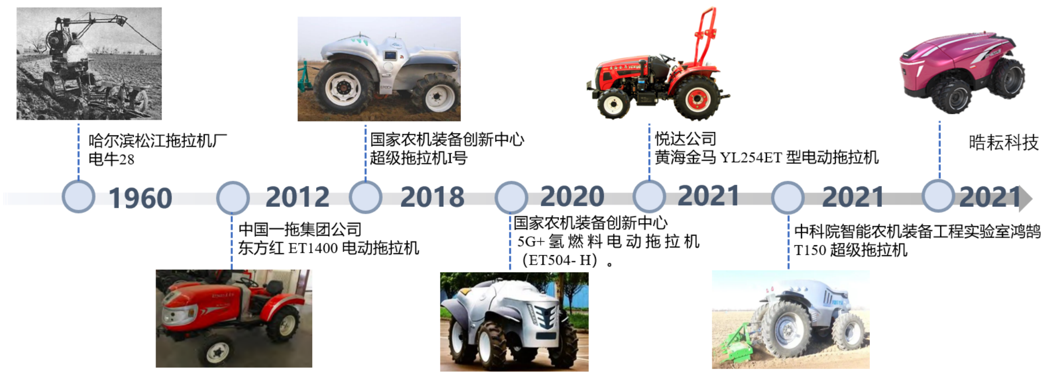

图 VI 国内拖拉机发展历程

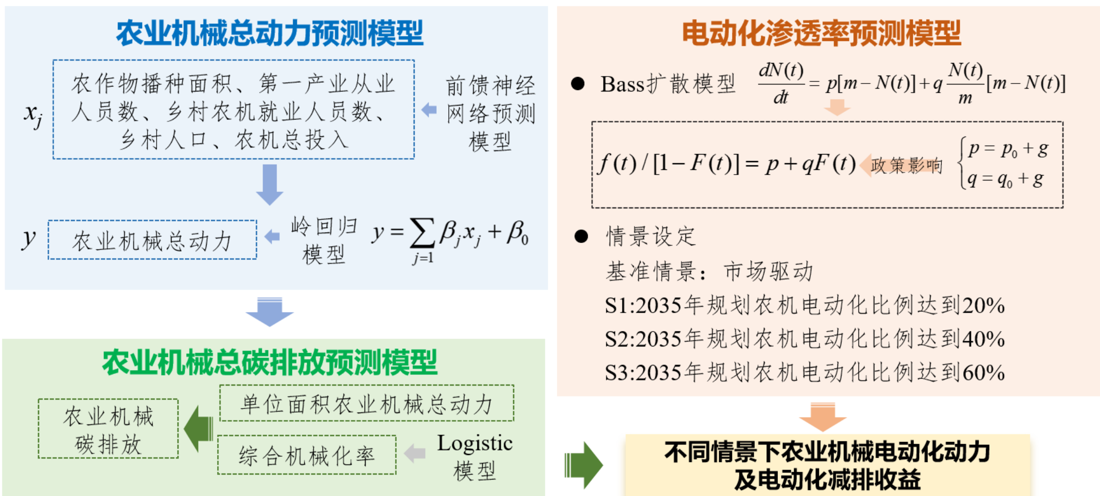

图 VII 农机碳排放收益预测模型

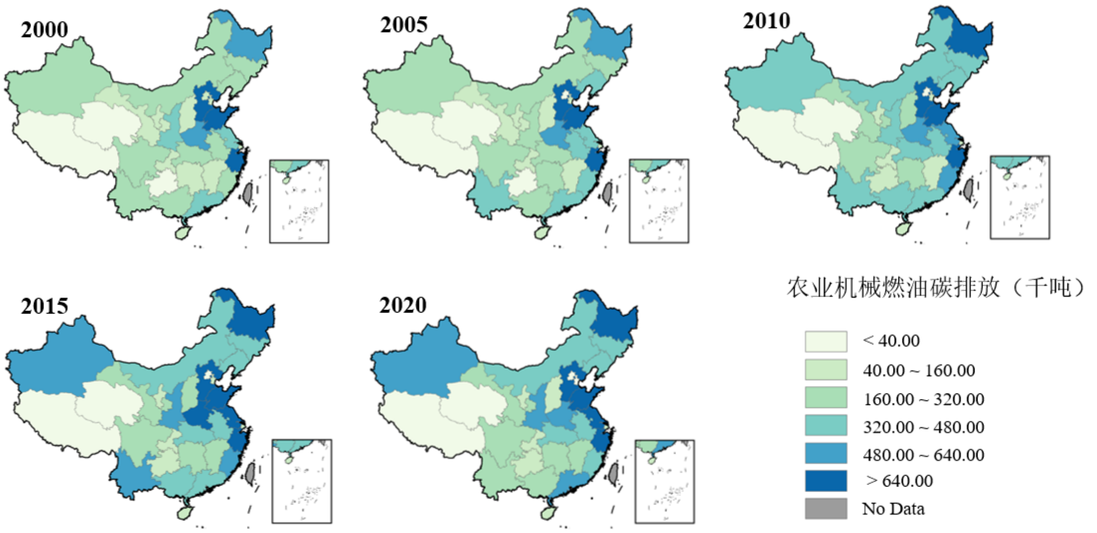

图 VIII 农业机械碳排放图

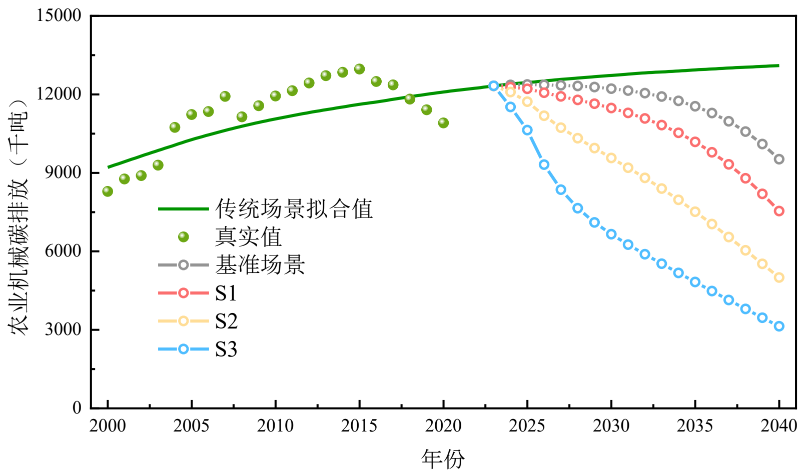

图 IX 不同场景下农机电气化的减碳收益

6. 与山东东营罗盖村达成示范村合作意向

- **罗盖村具有三大优势。**（1）罗盖村一定程度上代表中国未来的农村场景。面对农村老龄化和空心化的趋势，合村并居是未来农村的发展路径之一；（2）无需变压器扩容费用。罗盖村已经完成变压器扩容，村中两台变压器容量将近 1000kW，满足新型电力系统的需求；（3）当地政府与电网公司的配合度高，也已经和当地电网公司合作申请省科技项目。

- **示范村新型电力系统方案。**每个农宅屋顶安装 10-15kW 光伏，光伏电力直接送入户内满足电器和 5kWh 储电的需求，多余的电力送入村级母线，满足集中储电和周边地源热泵机组和农业生产负荷的需求。最后，多余的电力响应电网的调度送入电网。其中，罗盖村采用电动拖拉机作为集中储能。

- **示范村建设进度。**目前已申请山东电力科技项目，用于解决项目建设的成本。同时，已经确定了光伏板的投资，示范户的屋顶光伏铺设工作已经完成。示范村的设计方案和施工图纸也已经基本完成。

图 X 罗盖村卫星影像

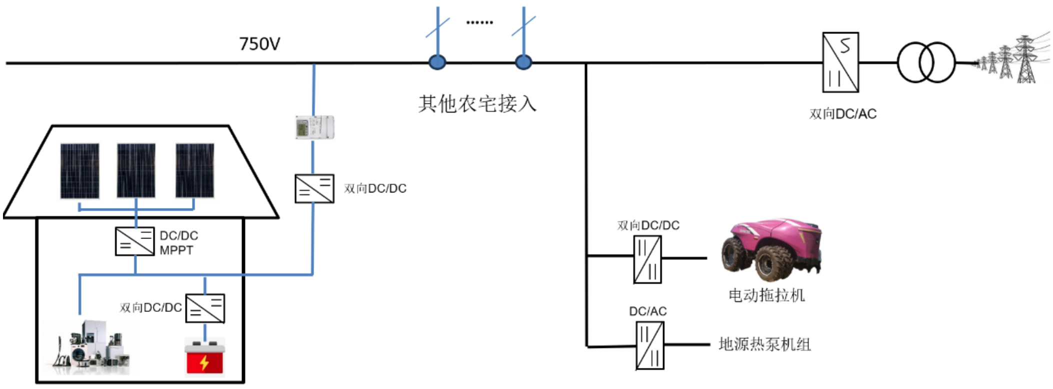

图 XI 罗盖村新型电力系统拓扑

7. 农村新型电力系统的商业模式

- **“政府引导，企业投资，农户参与”的融资方式。**新型电力系统共有四家参与方，分别是政府、国家电网、投资开发商、以及农户。其中，这几种角色可以相互重叠，一方承担多个角色。投资主体一般分为农户个人和企业两种，农户作为投资主体来说模式较为简单，项目建设的复杂度较小，需协调的相关方较少，回收期最短，但是农户普遍不具备投资能力。相较而言，企业作为投资开发商，运营过程中需要大量协调政府、金融机构的相关关系，投资能力强，但是回收期长。融资的金融机构主要负责建设资本提供和筹集，是整个分布式光伏项目的资金来源渠道，决定着商业模式中资金周转的有效性，其决定着商业模式是否能正常开展。政府主要负责制定并出台相关政策、行业发展规范，开展市场监管，

批准和发放各类补贴，同时出台相关的法律对其他的市场主体行为进行约束，化解市场中出现的争端和冲突，为分布式光伏发展营造良好市场氛围。

- **整合政策，集中发力。**现阶段由于市场机制还不完善，导致新型电力系统的经济性还不具备投资吸引力，这就需要结合政策上的优惠来吸引投资者参与。目前国家对于农村的政策，主要分为四类：1，扶贫政策。如光伏扶贫、旅游扶贫、家政扶贫等；2，基础设施补贴。如农网升级改造，危房改造；3，专项活动补贴。如清洁取暖、家电下乡、新能源建设以及农机具购买等；4，生活福利及其他。如农电电费补贴等。因此，农村新型电力系统涉及到多方面的政策补贴，如果多种补贴可以综合发放，则每个示范户至少可以获得 2 万元的政策优惠，进一步改善农村新型电力系统的经济性。

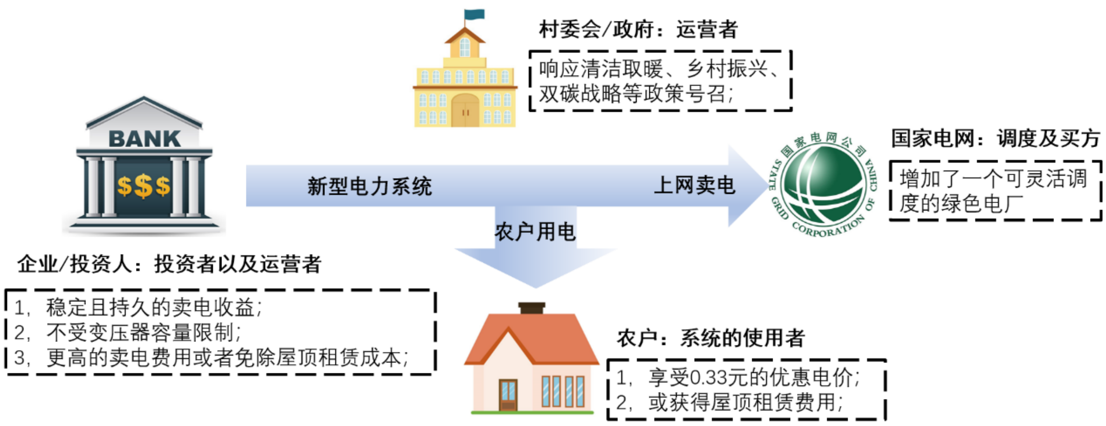

图 XII 新型电力系统参与角色分析

8. 农村新型电力系统的政策建议

- **动态电价是提高参与方积极性的重要动力。**目前限制农村新型电力系统很大的因素是电价，因为电力系统的收益来自于卖电，因此提升电价将会明显提高电力系统的经济性。但是，电价与民生直接相关，简单粗暴地提高电价会影响农户生活质量。因此，建议采用分时电价，提高非午间上网的电价，这有助于提高储能经济性，对于可以灵活响应电网调度的系统是一种正反馈奖励。同时，降低中午的上网电费和用电电费，引导农户加大高峰期的用电量，帮助促进光伏的就地消纳。同时，也可以在电交易中增加碳交易份额，从而增加可再生能源电力的经济性。

- **加大直流变换器、直流电器、电动农机与电动交通工具的补贴。**直流变换器是造成新型电力系统相比直接逆变系统投资成本更昂贵的主要原因。这就需要出台相关的政策进行对直流变换器以及直流电器进行补贴。

通过对这些直流设备的补贴支持可以提高市场需求，从而促进直流设备的产业升级发展。同样，对于农村潜在的储能设备，如电动汽车、电动农机的补贴也对于提高农村新型电力系统的经济性有积极的作用。需加快各类电动农机具和交通工具电气化工作，调整对农业装备的补贴政策，将目前对农林生产机械化方面的各项支持政策转为支持“油改电”。把农林业装备电气化任务纳入到我国农林业装备发展规划中。采用标准化模块电池，农机和车辆采用换电模式，可以使蓄电池充分发挥作用。从而全面推动农村新能源系统的建设和农机电气化的推广。

- **加强对农村电力系统上网的监管。**以村为单位，将全部农户屋顶、院子周边、农业设施、林地荒地具备铺设光伏的资源统一规划，“建档立卡、一村一策”，将电动农机具、电动车、农户采暖以及家电升级等需求综合考虑，采用光储直柔方式，分期分批统一建设。同时，加大对于分布式光伏系统的审查力度，制定光伏并网规范，如严格规定储能比例、系统灵活性、响应速度、自消纳率等参数，通过强制的标准提高分布式光伏系统的质量。同时应该在农村引导推广“优先自发自用，余电有序上网”的系统，逐步淘汰之前的分布式光伏直接逆变上网方案。

- **建设农村新型电力系统的交易平台。**加快分布式发电交易平台建设，使得投资安装光伏的农户可以“隔墙售电”。和城市地区建筑类型多样、用电计量计费复杂的情形不同，农户每家天然具备产销一体的属性，让农户实时感知简单的清洗电池板、系统别掉线，多余的电就能够卖钱，除了还贷款还能净赚一笔钱，可以使得光储直柔系统的后期运维成本最低。“隔墙售电”可彻底破解当前农村地区户用光伏系统中“农户袖手旁观、企业运维不起”的困境。

Executive Summary

1. Dilemma and Opportunities of Rural Energy Systems

- **Rural areas in China exhibit significant energy consumption in building sector.** Energy consumption in rural regions accounts for approximately one-fourth of the total building energy consumption in the entire society. The energy consumption in rural buildings includes the usage of 2.2 million metric tons of standard coal equivalent of commercial energy and the direct combustion of 90 million metric tons of biomass energy. Additionally, rural areas have the highest utilization rate of bulk coal in China, with an approximate consumption of 110 million metric tons of standard coal. The operational carbon emissions from rural buildings are estimated to be around 420 million metric tons, representing about 20% of the national building carbon emissions.

- **The energy consumption in rural areas of China has resulted in significant environmental costs.** As a major energy source in rural regions, the combustion of fossil fuels, especially for heating purposes in northern rural areas, has led to the release of a large amount of carbon dioxide and severe air pollution. The combustion byproducts of fossil fuels, such as PM2.5, nitrogen oxides, and carbon monoxide, pose serious health risks to indoor occupants. According to a report by the World Health Organization, in 2019, approximately 1.03 million people in China died due to air pollution, with 62% of these deaths occurring in rural areas.

- **The effectiveness of the rural "coal-to-electricity" and "coal-to-gas" conversion programs has been less than satisfactory.** Since 2017, China has implemented the "coal-to-electricity" and "coal-to-gas" projects in rural areas. However, due to a lack of comprehensive top-level design, the prices of natural gas and municipal electricity have become excessively high, leading to a situation where many households in most regions have reverted to using bulk coal after the subsidies ended. Therefore, achieving "carbon neutrality" in rural areas cannot be simply seen as an energy substitution project but rather as a complex endeavor that requires detailed and reliable planning. This includes scientific technological innovations, practical engineering applications, and comprehensive policy guidance. It necessitates comprehensive reforms and innovations in technology, policy, and business models.

- **The rural energy revolution is closely tied to national strategies.** In his speech at the 2020 United Nations General Assembly, President Xi Jinping announced China's commitment to peak carbon dioxide emissions before 2030 and strive for carbon neutrality by 2060. A State Council document emphasizes that after achieving poverty alleviation goals, the focus of

China's rural development shifts towards the comprehensive promotion of rural revitalization strategies. Rural energy transformation is a key means to promote rural industrial development and ecological governance, and it serves as an important foundation for realizing the rural revitalization strategy. Establishing a new type of energy system in rural areas is a crucial pathway to achieve carbon neutrality and serves as a cornerstone for promoting rural ecological governance and rural revitalization.

- **Rural areas possess spatial advantages for developing photovoltaic systems.** One of the key tasks in achieving carbon neutrality is transitioning from a carbon-based electricity system reliant on fossil fuels to a zero-carbon electricity system based on renewable energy sources. Therefore, decarbonizing energy consumption in rural areas requires comprehensive promotion of electrification in households and the utilization of renewable energy to replace thermal power generation. Rural areas have unique spatial advantages in developing renewable energy sources. According to satellite image recognition results, rural areas in China have abundant roof space, with a potential for installing 1.9 billion kilowatts of photovoltaic capacity. The annual electricity generation from photovoltaic systems can reach 2.5 trillion kilowatt-hours, which is three to four times the projected electricity demand after achieving comprehensive electrification in rural areas. Therefore, the development of a new power system in rural areas, with distributed photovoltaics as a core component, can fully leverage the immense photovoltaic potential in rural areas, transforming them from traditional energy consumers to energy producers.

2. China's rural areas are striving to establish a new type of power system based on rooftop PV

- **The traditional method of direct grid-tied photovoltaic (PV) systems cannot facilitate the energy transition in rural areas.** Currently, the operational model of PV systems in rural areas is as follows: developers lease rooftops from households to install PV panels, and the PV-generated electricity is directly fed into the grid, while households still rely on the grid for their electricity needs. This type of PV system faces three main issues: Inequity: Due to limited transformer capacity, only a few "early adopter" households in each village can enjoy grid access. This approach wastes the vast PV potential of rural rooftops. Insufficiency: This system separates electricity generation and consumption into two separate systems. Developers gain profits from selling electricity, while farmers do not reap the benefits. Moreover, farmers do not directly benefit from PV electricity, and this type of PV system does not effectively change the existing energy structure in rural areas. Imbalance: PV generation is subject to randomness and fluctuation, and direct grid integration can lead to the generation of surplus electricity that cannot be effectively utilized. It also fails to leverage rural energy storage resources, resulting in the wastage of a significant amount of peak-shaving power resources. Therefore, the existing PV systems are incapable of leading the decarbonization of energy consumption in rural areas. Rural areas require a new power system that allows farmers to enjoy PV electricity and brings tangible benefits to them.

- **The rural “Photovoltaic - Energy storage - DC - Flexible load” power system promotes the transformation of the rural energy structure.** To overcome the issues of inequity, insufficiency, and imbalance brought by traditional rural PV systems, the “Photovoltaic - Energy storage - DC - Flexible load” power system has emerged. Its fundamental principle is prioritizing self-consumption and orderly grid export of excess electricity. The operation of this system is as follows: PV electricity first satisfies the electricity demand of rural households and charges the energy storage devices. Any surplus electricity is then dispatched in an orderly manner to the grid. Compared to traditional rural PV systems, this type of system offers three advantages: Reduced pressure for transformer capacity expansion: Since a significant proportion of PV electricity is consumed locally, the pressure for transformer capacity expansion is alleviated, allowing more households to participate in the system. Full utilization of rural energy storage advantages: This system leverages rural energy storage capabilities, ensuring that PV electricity is not wasted and does not increase the grid's dispatch pressure. Direct utilization of PV electricity by households: Households not only benefit economically from using PV electricity but also drive comprehensive rural electrification and decarbonization of energy consumption in rural areas.

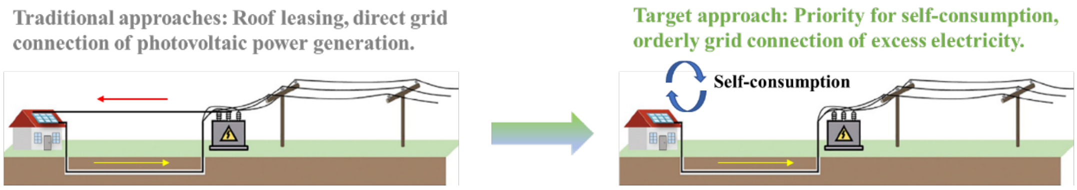

Figure I Comparison between “Photovoltaic - Energy storage - DC - Flexible load” power system and traditional photovoltaic power system

3. Design Scheme for Rural PEDF Power System

- **The challenge of the rural PEDF power system lies in addressing the mismatch between PV electricity and household loads.** There is a significant mismatch between PV electricity and household electricity demand, which is the biggest challenge faced by the rural PEDF power system. When examined on an hourly time scale, it can be observed that the inconsistent characteristics of PV generation and household electricity demand result in PV electricity being unable to consistently meet the needs of households. The key to solving this problem lies in control strategies and energy storage technologies. Energy storage enables the transfer of PV electricity, allowing households to meet their electricity needs during nighttime and cloudy/rainy days through the stored energy. Control strategies determine the operational patterns of the system, ensuring smooth operation according to the intended plan.

- **The topology of the PEDF power system needs to be tailored to local conditions.** Determining the system's topology is the foundation of designing a rural PEDF power system. Currently, the topology of rural “Photovoltaic - Energy storage - DC - Flexible load” power systems can be broadly categorized into three types. Different topology options result in varying levels of generation efficiency, transmission losses, equipment capacity, control methods, and investment costs. Each option has its advantages and disadvantages. Therefore, in practical projects, it is necessary to consider local factors such as electricity prices, equipment costs, grid connection policies, flexibility goals, etc., and conduct an economic comparison to select the most cost-effective option.

- **The PEDF power system requires a decentralized adaptive control method.** Due to the characteristics of rural buildings being "large in quantity and dispersed in area," traditional centralized control methods are difficult to adapt to rural scenarios. In the case of a direct current (DC) system, voltage is the simplest and most important operational parameter. The voltage signal can be utilized as a control signal to modify the operating conditions of devices. Specifically, the voltage signal at the sensing contact of power electronic devices in the system can change their operating state based on the voltage level. This is a decentralized controller-less control method where devices make adaptive adjustments based on the voltage signal at their location to maintain stable system operation.

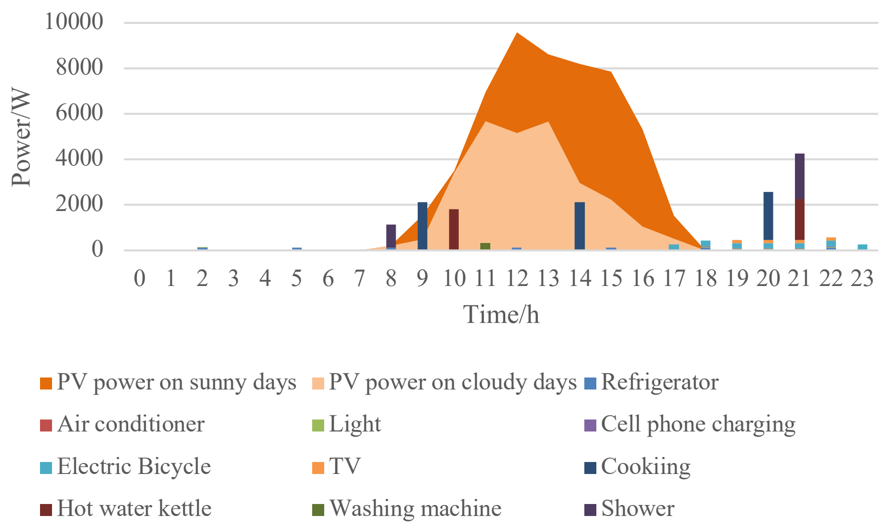

Figure II Hourly comparison of photovoltaic power and energy used by farmers

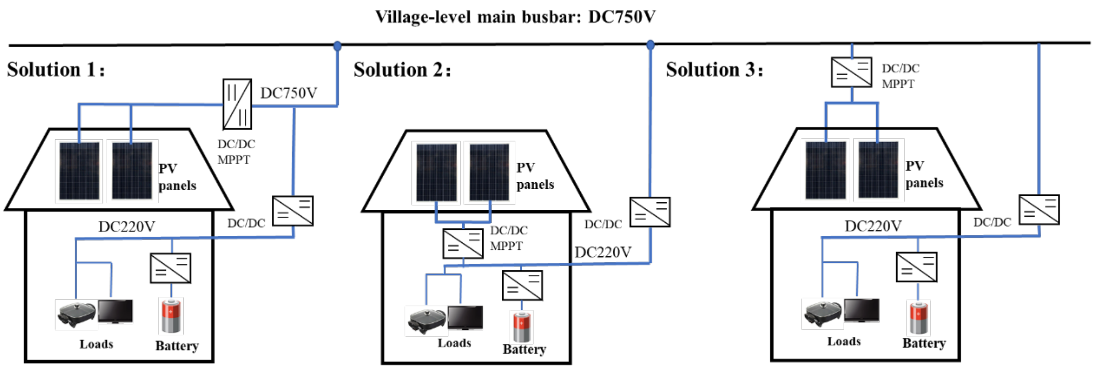

Figure III Common farmhouse photovoltaic topology

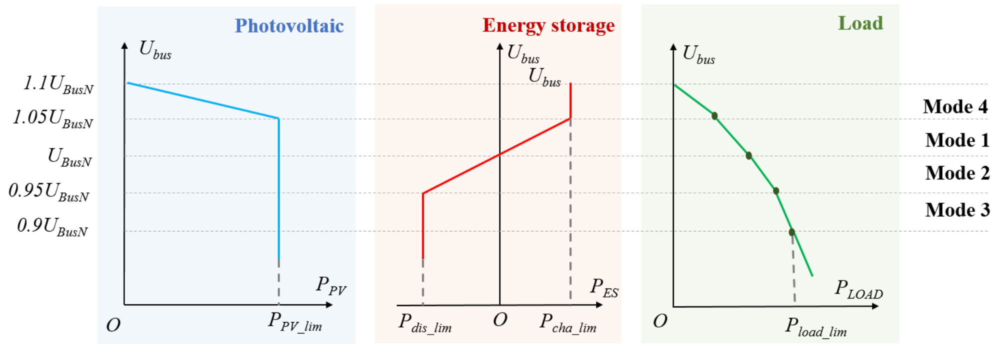

Figure IV Based on the principle of bus voltage control

4. Rural PV Heating Scheme to Serve Room Functions

- **A low-cost energy storage solution is needed for rooms that are in use throughout the day.** For a bedroom, which is occupied all day, there is a stable heat load requiring heating at any given moment. However, photovoltaic (PV) power is unable to meet the heating demand of the room during nighttime and cloudy/rainy days. Therefore, it is necessary to transfer the heat generated during sunny days to match the room's heat load during nighttime and inclement weather. This heat transfer process can be achieved through energy storage. However, the cost of electrical energy storage is prohibitively high and difficult for rural households to afford. Traditional thermal energy storage technologies are expensive and require large amounts of space, making them impractical for implementation in rural residences. In this regard, heat storage in walls can be employed as a solution. Red bricks, with their low cost, can serve as a medium for heat storage, while occupying minimal space in the walls, thereby not significantly reducing the living space for households. The heating endpoint can be achieved by using photovoltaic direct-driven electric heating wires. Since the operation of the heating wires does not require voltage or power stability control, it reduces the cost of control equipment. Through testing, it has been determined that the average black globe temperature in the room during winter reaches 16°C, meeting the thermal comfort requirements of rural households.
- **A low-cost control strategy is required for rooms with intermittent use.**

For rooms such as the kitchen and living room, which are intermittently used, adopting a thermal storage method would reduce the flexibility of system control and waste thermal storage resources. Therefore, using a photovoltaic-driven heat pump is a suitable approach for heating intermittently used rooms. The rapid temperature rise of the heat pump system allows for quick response to changes in the number of occupants, making it suitable for such rooms. However, such a system needs to overcome the fluctuations in photovoltaic power in order to control the stability of output power and voltage. In the PEDF power system, a control method utilizing voltage signals can be employed. Test results have shown that during the daytime, almost all the power for the heat pump comes from photovoltaic power, and the system maintains output power to meet the electrical demand of the heat pump at all times.

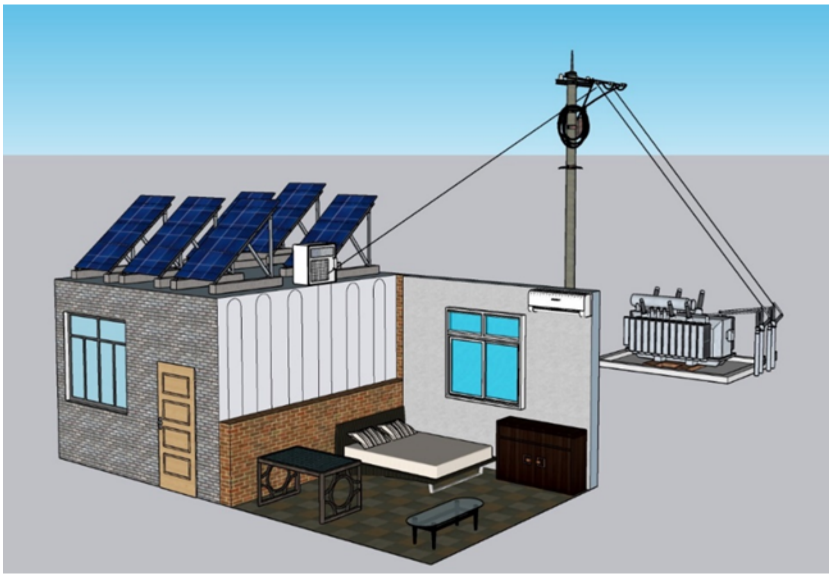

Figure V Photovoltaic heating system based on wall heat storage

5. Electric Agricultural Machinery to Provide Energy Storage Resources for Rural PEDF Power Systems

- **The electrification of agricultural machinery is an inevitable trend for the future development of agricultural mechanization.** With the comprehensive electrification of rural areas, the electrification of agricultural machinery will become a potential energy storage resource, providing regulation and storage capabilities for the new rural power system. In the 1980s, electric tractors began to appear worldwide. Over the past 130 years, electric tractors have gone through two major phases: grid-powered and battery-powered. In the 21st century, with the deepening energy crisis and the rapid development of new energy technologies, electric tractors have entered a period of rapid growth, characterized by the following aspects: Integration of advanced power electronics technology, further improving the lightweight and responsiveness of electric tractors. The emergence of extended-range electric drive technology has enhanced the adaptability of electric tractors for high-power field operations, promoting the development of high-power electric tractors. Significant advancements in battery technology have greatly increased the rated power and endurance of electric tractors.

- **The process of electrifying agricultural machinery in China is still in its early stages.** The development of electric tractors in China started relatively late, and it wasn't until 1960 that the Harbin Songjiang Tractor Factory successfully produced the first electric tractor in the country. Afterward, there was a relatively stagnant period of development. It was only after 2010 that electric agricultural machinery in China experienced a rapid growth phase. With improvements in power batteries, electric drive technology, overall machine, and component control technology, as well as traction, power, and economic performance of tractors, significant progress has been made in the research and development of electric tractors in China. However, the actual production and application of electric tractors are still very limited, and there is still considerable room for improvement in areas such as overall weight, endurance time, and rated power of electric tractors.
- **Agricultural machinery electrification provides abundant energy storage resources.** By investigating the working duration and power range of different traditional agricultural machines and considering the parameters of commonly used lithium iron phosphate batteries, the battery capacity of commonly electrified agricultural machines can be predicted. Tractors have the largest energy storage potential, ranging from 11 to 589 kW·h, which is determined by their combined characteristics as power devices. Crop protection machinery and cultivation machinery, due to their complementary use, have relatively large overall energy storage potentials, ranging from 0.04 to 71 kW·h and 8 to 14 kW·h, respectively. The energy storage potential of transportation machinery is between 6 and 165 kW·h. Several types of agricultural machinery, such as sprayers, sprayers, transplanters, forage machines, micro tillers, and garden management machines, have relatively small energy storage capacities, within 10 kW·h. However, they are commonly found in rural households and can essentially meet the energy storage scheduling needs of household-level PEDF power systems.
- **The energy storage methods of electric agricultural machinery can adapt to different rural scenarios.** For the current usage patterns of agricultural machinery at the household level, production-side electric equipment such as lawnmowers, sprayers, and micro tillers can provide at least 9 kW·h of energy storage potential. Transportation-side electric equipment such as electric bicycles, electric tricycles, and low-speed electric vehicles can provide at least 9.5 kW·h of energy storage potential. Therefore, electric agricultural machinery can provide at least 20 kW·h of energy

storage potential for household-level rural new energy systems, meeting the energy storage scheduling needs of farmers. In the scenario of future large-scale land management, the variety of large-scale electric agricultural machinery will significantly increase. Household-level electric agricultural machinery equipment and the equipment used in large-scale operations will interact orderly and extensively through battery cabinets and assembled batteries.

- **The electrification of agricultural machinery will make a significant contribution to carbon reduction in rural areas.** By constructing a top-down model, the carbon emission reduction benefits brought by the electrification of agricultural machinery under different planning scenarios can be predicted. The model predicts that by 2025, the total power of agricultural machinery will be 1,136,877.7 MW. Only with market-driven promotion, the penetration rate of electric agricultural machinery in China develops relatively slowly, reaching 26.04% by 2040, resulting in a reduction of 357.81 kilotons of CO_2 emissions. In the high-speed development scenario, by 2035, the electrification of agricultural machinery will bring a reduction of 357.81 kilotons of CO_2 emissions, which is 5.83 times higher than the market-driven scenario. Active policy guidance to promote the electrification of agricultural machinery can yield substantial carbon emission reduction benefits.

- **The challenges of agricultural machinery electrification lie in battery and motor technology.** The biggest technical challenge in agricultural machinery electrification is the battery. Electric agricultural machinery requires high power and has specific demands for operating duration, thus the battery needs to have a large capacity and high energy density. Additionally, agricultural machinery generates strong vibrations during operation, which imposes high requirements on battery safety and heat dissipation performance. Due to the unique working environment, there are also high demands on the performance of electric motors. Firstly, they need to withstand harsh working conditions and have strong dust and water resistance. Secondly, they should have a wide speed range to meet different operating conditions. Thirdly, they should be able to handle sudden load changes and have an overload capacity of more than double the rated load. Lastly, in practical use, they should possess high torque and high instantaneous output power.

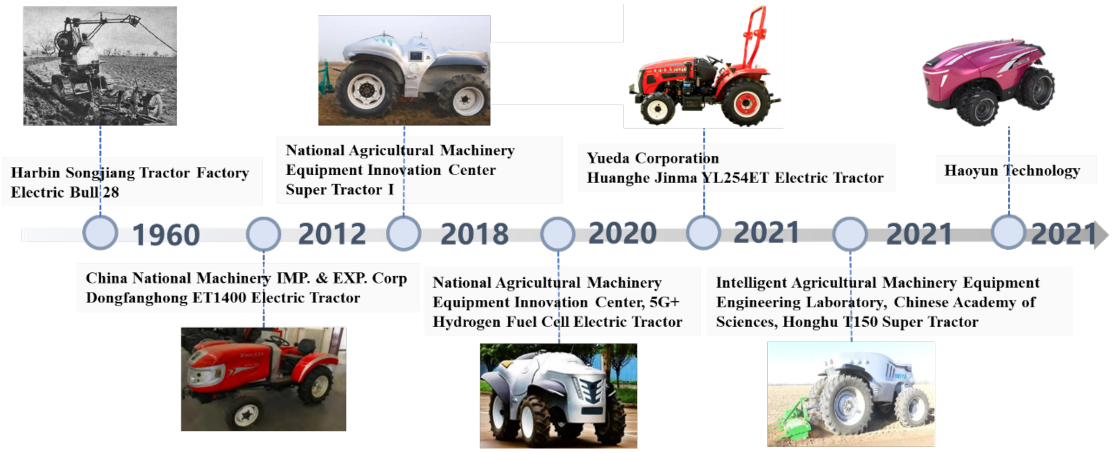

Figure VI Domestic tractor development history

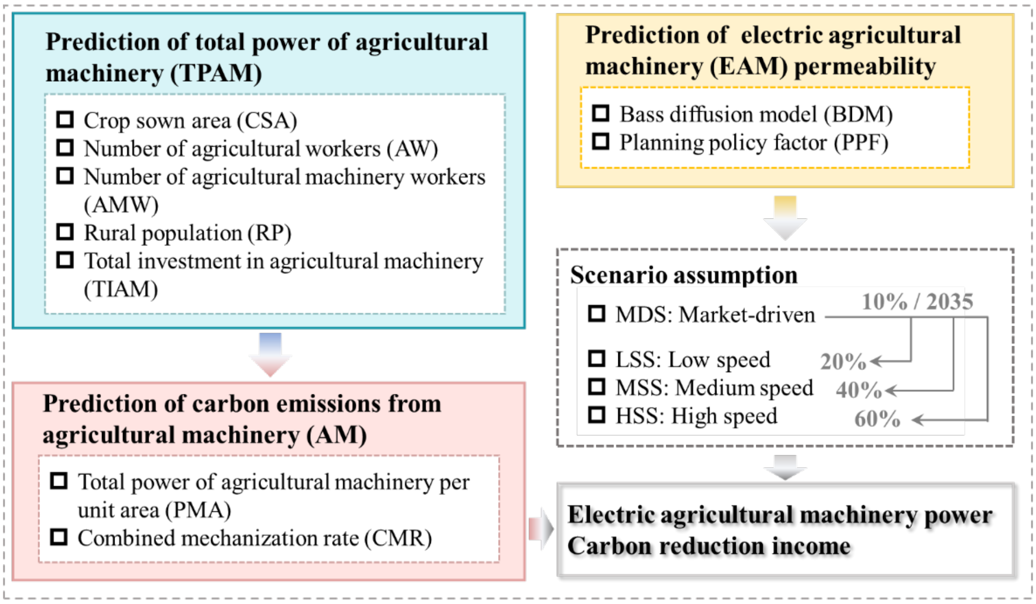

Figure VII Agricultural machinery carbon emission income forecast model

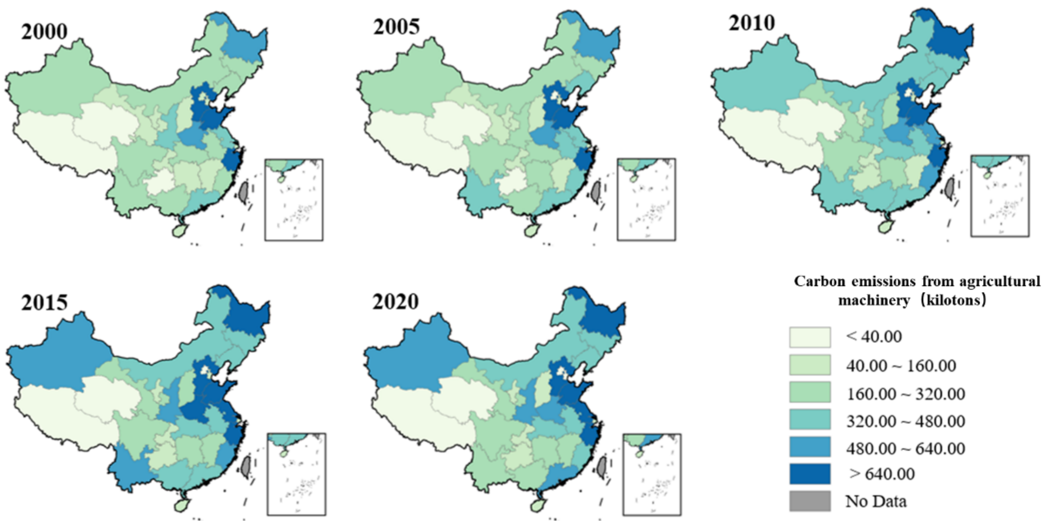

Figure VIII Carbon emission map of agricultural machinery

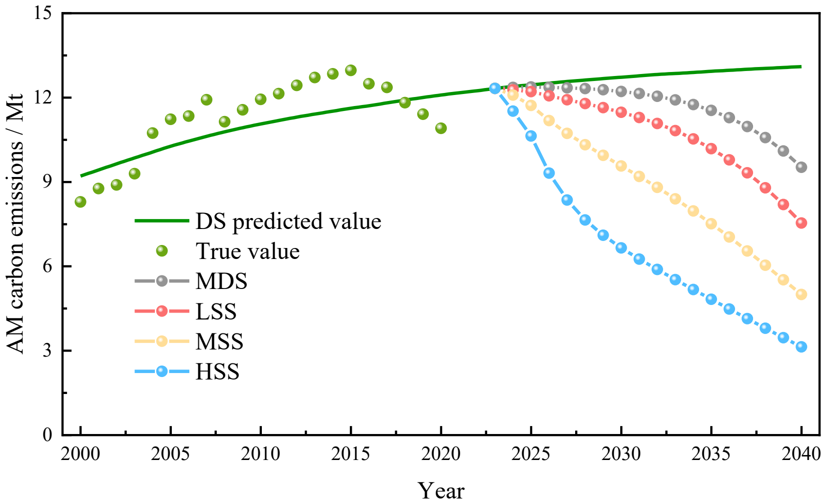

Figure IX Carbon reduction benefits of electrification of agricultural machinery under different scenarios

6. Intention to Collaborate with Luogai Village in Dongying, Shandong Province as a Demonstration Village

- **Luogai Village has three major advantages.** (1) Luogai Village represents to a certain extent the future rural scene in China. Facing the trend of aging and hollowing out of the countryside, merging villages and living together is one of the development paths for the future of the countryside. (2) No need for transformer capacity expansion costs: Luogai Village has already completed transformer capacity expansion. The village has two transformers with a combined capacity of nearly 1000 kW, which meets the requirements of the new power system. (3) High cooperation between the local government and the power grid company: Luogai Village represents a future rural living model in China, and there is a high level of cooperation between the local government and the power grid company.

- **Demonstration Village PEDF Power System Scheme:** Each rural household is equipped with 10-15 kW photovoltaic (PV) panels installed on the rooftops. The PV electricity is directly supplied to meet the household's electrical needs and provides 5 kWh of energy storage. Excess electricity is fed into the village-level busbar to meet the demands of centralized energy storage, surrounding ground-source heat pump units, and agricultural production loads. Finally, any surplus electricity is dispatched to the grid in response to grid scheduling. In Luogai Village, an electric tractor is adopted as the centralized energy storage solution.

- **Progress of the demonstration village construction:** Currently, an application has been submitted for the Shandong Electric Power Technology Project to address the construction costs of the project. Additionally, investments for the photovoltaic panels have been secured, and the installation of rooftop PV panels in the demonstration households has been completed. The design scheme and construction drawings for the demonstration village have also been largely finalized.

Figure X Satellite image of Luogai village

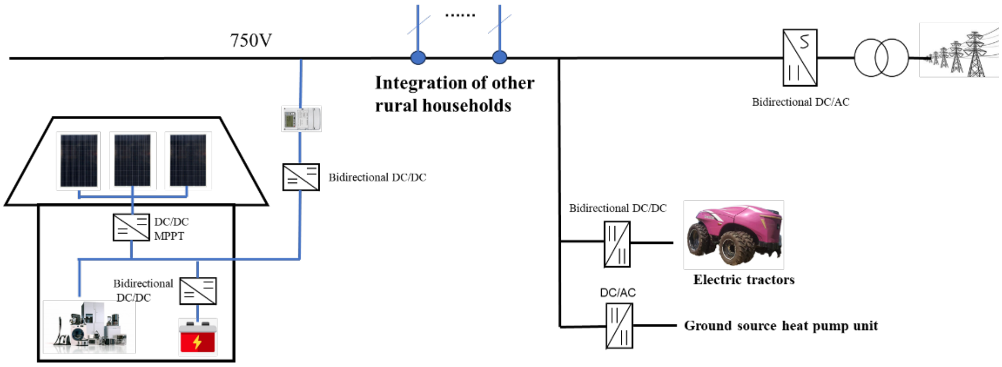

Figure XI Topology of the PEDF power system in Luogai Village

7. Business Model for Rural New Power Systems

- **"The government guidance, corporate investment, and farmer participation" financing model.** The new power system involves four participating parties: the government, the State Grid Corporation, investment developers, and farmers. These roles can overlap, with one party taking on multiple roles. The investment entities generally consist of individual farmers and businesses. For farmers, the investment model is relatively simple, with less complexity in project construction and fewer stakeholders to coordinate with. The payback period is shorter, but farmers generally lack investment capacity. On the other hand, businesses, as investment developers, require extensive coordination with the government and financial institutions during the operational phase. They possess stronger investment capability but have a longer payback period. Financial institutions involved in financing primarily provide and raise capital, serving as the funding source for the entire distributed photovoltaic project. They determine the effectiveness of capital turnover in the business model, which in turn affects the normal operation of the business model. The government's role primarily involves formulating and implementing relevant policies and industry development standards, conducting market supervision, and approving and distributing various subsidies. Additionally, the government enacts relevant laws to regulate the behavior of other market entities, resolves disputes and conflicts that arise in the market, and creates a favorable market environment for the development of distributed photovoltaics.

- **Integrating policies and focusing efforts.** Currently, due to imperfect market mechanisms, the economic viability of the new power system lacks investment attractiveness. Therefore, it is necessary to combine policy incentives to attract investors. Currently, the national policies for rural areas can be classified into four categories: (1) poverty alleviation policies, such as photovoltaic poverty alleviation, tourism poverty alleviation, and domestic service poverty alleviation; (2) infrastructure subsidies, including rural grid upgrades and renovation of dilapidated houses; (3) special activity subsidies, such as clean heating, appliance distribution in rural areas, new energy development, and agricultural machinery purchases; (4) living welfare and other subsidies, such as electricity tariff subsidies for rural households. Therefore, the rural new power system involves various policy subsidies. If multiple subsidies can be combined and distributed comprehensively, each demonstration household can receive at least 20,000 RMB in policy incentives, further improving the economic viability of the rural new power system.

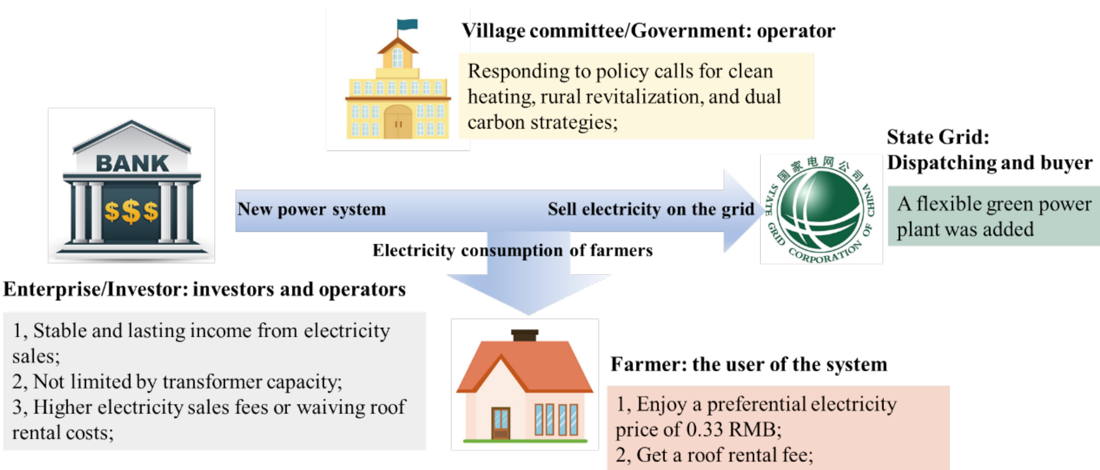

Figure XII New power system participation role analysis

8. Policy Recommendations for Rural PEDF Power Systems

- **Dynamic electricity pricing is an important incentive to increase the motivation of participants.** Currently, a significant constraint on the rural PEDF power system is the electricity price, as the system's revenue comes from selling electricity. Therefore, increasing the electricity price would significantly improve the economic viability of the power system. However, electricity prices are directly linked to people's livelihoods, and a blunt increase in electricity prices could affect the quality of life for rural households. Therefore, it is recommended to implement time-of-use pricing, with higher prices during non-peak hours. This approach helps improve the economic viability of energy storage and serves as a positive feedback reward for systems that can flexibly respond to grid dispatch. Simultaneously, reducing the electricity fees during midday and peak consumption periods can encourage rural households to increase their electricity usage during those times, thus facilitating the local absorption of photovoltaic energy. Additionally, incorporating carbon trading into electricity transactions can enhance the economic viability of renewable energy electricity generation.

- **Increasing subsidies for DC converters, DC appliances, and electric agricultural machinery and vehicles is essential.** DC converters are the main reason why the investment cost of the PEDF power system is higher compared to direct inversion systems. Therefore, relevant policies should be introduced to provide subsidies for DC converters and DC appliances. Subsidies for these DC devices can boost market demand and promote the upgrading and development of the DC equipment industry. Similarly, subsidies for potential energy storage devices in rural areas, such as electric vehicles and electric agricultural machinery, have a positive impact on improving the economic viability of the rural new power system. Efforts should be made to accelerate the electrification of various types of electric agricultural machinery and vehicles and adjust the subsidy policies for agricultural equipment to support the transition from fossil fuel-based machinery to electric alternatives. The electrification of agricultural and forestry equipment should be incorporated into China's development plans for agricultural and forestry equipment. The use of standardized modular batteries and adopting a battery-swapping model for agricultural machinery and vehicles can fully utilize the battery's capacity. This will comprehensively promote the construction of rural renewable energy systems and the widespread adoption of electric agricultural machinery.

- **Strengthening the regulation of rural power system grid connection is crucial.** The planning of photovoltaic resources should be unified at the village level, considering all households' rooftops, surrounding yards, agricultural facilities, and unused land. A comprehensive approach should be taken, considering the demand for electric agricultural machinery, electric vehicles, household heating, and appliance upgrades. The construction should be carried out in a phased and unified manner, adopting a flexible approach of integrating solar power generation, energy storage, and grid connection. Additionally, it is important to enhance the scrutiny of distributed photovoltaic systems and establish standards for grid integration. Parameters such as energy storage ratios, system flexibility, response speed, and self-consumption rates should be strictly regulated. By enforcing these standards, the quality of distributed photovoltaic systems can be improved. Furthermore, it is advisable to guide and promote the system of "priority for self-consumption, orderly grid connection of excess electricity" in rural areas.

This approach gradually phases out the previous practice of direct inversion grid connection for distributed photovoltaic systems.

- **Establishing a trading platform for the rural PEDF power system is crucial.** The development of a distributed generation trading platform should be accelerated, allowing households that invest in photovoltaics to engage in "peer-to-peer" electricity sales. Unlike the diverse building types and complex metering and billing systems in urban areas, rural households naturally possess the attribute of integrated production and consumption. By enabling rural households to have real-time awareness of simple tasks like cleaning solar panels and system connectivity, they can sell excess electricity and earn additional income, which can offset loan repayments and minimize the long-term operation and maintenance costs of "Photovoltaic - Energy storage - DC - Flexible load" systems. This "peer-to-peer" electricity trading can effectively address the current challenges of rural household photovoltaic systems, where households are passive and rely on external companies for operation and maintenance.