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Where Electrification Improves and Where It Struggles: A Renewables-and-Materials View of Small Cars and Domestic Heating

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Abstract. As more and more technology advancement of transportation and electrification of heating system, residents nowadays usually had the less demand for using the fossil fuel which causes the carbon emission. For instance, most people's vehicles had converted from ICE (internal combustion engine) vehicles to the BEVs (Battery electric vehicles). Another example, domestic heating pumps, use electricity instead of using fossil fuel (natural gas, propane, heating oil, charcoal etc.) nowadays to transfer heat from a cool space to a warm space and reverse this process if in summer. Electrification refers to the source of generating the electricity and their usage are renewable such as photovoltaic, wind electricity, hydrogen-powered electricity etc. These source of electricity can supply the electric vehicles and the electric heat pumps sufficiently. However, the cost of source of generating the electricity and technology impede the electrification. For materials perspective, like battery, electromotor, conductors & insulators, heat exchange, and refrigeration materials. These materials can determine the efficiency, energy density and the life span. Nevertheless, these materials are also limited and difficult to manufacture. Thus, this paper will provide the clear and executable ideas for the strategies and material selection of small cars and heat pump renovations in electrification and explain the limitation in mechanism perspective.

Keywords: Electrification, Energy, Renewable Materials, Small Cars, Domestic Heating

1. Introduction

Electrification is widely proposed as a cornerstone of climate mitigation, particularly in transport and buildings - two sectors that together account for a large share of global final energy use and direct CO2 emissions. In principle, shifting end-uses to electricity enables higher device-level efficiency (e.g., electric drivetrains and heat pumps) and unlocks deep decarbonisation as power systems add renewables. In practice, however, the environmental benefit of electrification depends on where the electricity comes from, when the load is served, and what materials are required to build and operate the technologies at scale [1]. This paper will focus on two high-impact, technologically mature applications: small passenger cars and domestic heating (space and water). Both have commercially available electric options, established supply chains, and standardised components [1].

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We take a renewables-and-materials perspective to answer two questions: Where does electrification deliver clear efficiency gains and emissions reductions today? Where does it struggle because of temporal mis-match with renewable generation, infrastructure bottlenecks, or material constraints?

Where electrification improves. Recent reviews consistently report that BEVs achieve higher energy-use efficiency at the vehicle level than internal-combustion cars and can reduce lifecycle greenhouse-gas emissions when powered by grids with moderate to low carbon intensity. For example, regard to small passenger cars, there are a range from 39% to 67% WTW (Well to Wheel) efficiency to EVs which possesses higher WTW efficiency than ICE with a range from 11% to 27% [2]. For buildings, literature highlights that heat pumps deliver substantially more useful heat per unit of electricity than resistance heating or fossil boilers across typical operating conditions, with further gains from insulation and basic demand management [3].

Where electrification struggles. Evidence also shows variability in realised benefits. System-level outcomes depend on the carbon intensity of electricity, the timing of demand (daily peaks for vehicles; winter peaks for heating), and infrastructure readiness such as home/public charging, local network capacity and building fabric [1]. Reviews further note potential constraints and trade-offs on the materials side, for example the availability and sourcing of battery minerals (lithium, nickel) and the copper needed for motors and grids, as well as recycling routes and design choices that can ease these pressures [4]. Cost, consumer behaviour and policy support shape uptake and performance in practice [5].

Taking a renewables-and-materials perspective, this paper synthesises existing reviews to outline (i) situations where small-car and domestic-heating electrification already delivers clear efficiency and emissions benefits, and (ii) situations where outcomes are mixed and depend on grid decarbonisation, demand-side measures, or materials considerations. The paper collates common findings, notes points of disagreement, and summarises practical levers (e.g., improving building envelopes, managed charging, and recycling) highlighted by prior literature. The aim is to provide a concise, evidence-based overview rather than new modelling.

2. Literature review

2.1. Small passenger cars

Small passenger cars, the smallest category and the most common transport all over the world, contributing the highest use of energy in all over the transport. Nowadays, small cars have two types which are ICE (internal combustion engines) vehicles and BEVs. In this essay, we would prefer BEVs much more rather than ICE vehicles because of fewer carbon emission. However, BEVs are not promoted all over the world. Instead, most countries are still using the ICE vehicles due to the cost issue. In this case, we will discuss the limitations of BEVs and where BEVs can improve in terms of energy type usage and materials use.

2.1.1. Power feeding mechanism

As the quick development of electric small cars technology, more and more people choose the BEVs as their way of travel. For most BEVs, they all belong to the new energy, referring to energy derived from non-fossil fuel sources with a minimal environmental footprint. These new source of energy include solar photovoltaic, wind, geothermal, and sustainable biomass energy. These will be used in most BEVs, where the electricity is stored in batteries. However, these source of electricity are

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costly due to the high initial investment because of complex engineering, materials, and integration challenges. Furthermore, the technology of batteries is not enough mature nowadays because of the cost.

Base on this, the reason why batteries used in EVs have the limitations is that their energy density (Energy density = energy / volume) is much lower than ICE vehicles and the cycle life which refers to the number of complete charge & discharge cycles a battery can undergo before its capacity drops to a certain percentage (usually 80%) of its original capacity, is limited [7]. For energy density perspective, gasoline and diesel are hydrocarbons. Their energy is released through a highly exothermic chemical reaction (combustion) with oxygen from the air. The battery doesn't need to carry the oxidizer; it's pulled from the environment.

In addition, most BEVs have their dispatching, referring to the intelligent control and scheduling of when and how electric vehicles charge and, crucially, discharge their batteries to provide services to the power grid.

2.1.2. Materials and devices

This section mainly describes the trade-offs in battery design. Achieving high energy density often comes at the expense of fast-charging capability and the number of cycles [8]. They undergo significant expansion and contraction during charging & discharging, leading to cracking and degradation of the electrode structure. They also react more easily with the electrolyte, forming a less stable solid-electrolyte interphase (SEI), which consumes active lithium and reduces capacity permanently. For small cars, they might rely on public fast charging, this creates a difficult engineering compromise due to the cost issue [8]. Thus, government should play an important role on constructing more fast-charging charger.

Furthermore, this paper discusses the entire energy management chain [9]. It points out that the efficiency of the power conversion system (Inverter, the heart of the powertrain, converting from the battery's DC (Direct Current) into the AC (Alternating Current) that needed to drive the motor. This conversion process is not 100% efficient due to heat loss.) is critical for overall vehicle efficiency [9]. In small cars where every watt-hour counts, using less advanced semiconductor materials can directly limit the achievable range [9].

In addition, one of a main barrier to the electrification of small cars is the charge rate. This is because the movement ability of ions in cathode materials and the thermodynamic instability of electrolytes at high voltages are fundamental materials science barriers that prevent the widespread adoption of extremely fast charging, a feature that would greatly benefit small EVs [10]. During fast charging, people are trying to force a massive number of lithium ions to exit the cathode and rush to the anode all at once. If the ions can't physically move through the cathode material fast enough, it creates a logjam. Therefore, the newer and more advanced batteries with higher charging rate and higher energy capacity, are required to address this issue.

2.2. Residential heating

In the past, residents used fossil fuel to access the heat in the winter, resulting one part of the highest carbon emission. Nowadays, more and more heating system are transferred from the heat system provided by fossil fuel into electric-based heating. The heat pump, for example, is a revolutionary technology on heating electrification for most homeowners because it doesn't create heat. Even when it's cold outside, there is still thermal energy in the air. A heat pump uses a refrigerant cycle to extract that heat from the outdoor air (or ground) and transfer it inside to heat your home. In the

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summer, the process reverses, acting as an air conditioner. Nevertheless, its initial investment for a heat pump system is typically higher than replacing a like-for-like gas furnace. Therefore, we will explain where the electrification of residential heating is impeded and where it can improve or to address this issue.

2.2.1. Power feeding mechanism

This section of paper will discuss the challenges of integrating large amounts of intermittent wind power and highlights the importance of coupling the power sector with the heating sector to provide flexibility [11]. The task of integrating high levels of wind power into the electrical grid is a big challenge, impacting the entire energy network and comprehensive solutions. One such solution is sector coupling, specifically linking electricity production with heating systems. This involves using excess renewable electricity to heat water, which can be stored in massive insulated tanks (a form of thermal energy storage) or sent through distinct heating networks. These systems should provide an essential flexibility when the amount of electricity consumption is high with the sufficient wind energy, facilitating the speed of achieving the equilibrium point of demand and supply.

On large-scale thermal storage, it covers technologies like borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES) which are both crucial for seasonal storage of summer solar heat for use in winter [12]. These technologies are not just niche ideas but are key factors for solving the biggest problem in renewable heating - the seasonal mismatch between when we have abundant solar heat in summer and when we actually need it in winter. By providing a way to store large amounts of energy for months, this makes the decarbonisation of heating for the whole cities not just a theoretical possibility, but a practical engineering challenge.

In terms of dispatching of domestic heating, it will also quantitatively demonstrate how a group of heat pumps can be ingeniously scheduled to integrate wind energy by shifting their power consumption to periods of high wind energy availability [13]. A single heat pump's energy shift is negligible to the grid. However, the combined load of hundreds or thousands of heat pumps in a district or city represents a massive, flexible energy demand block. This "group" essentially acts as a VPP (Virtual Power Plant). Instead of a power plant generating more electricity when needed, this group reduces or shifts its consumption on command, which has the same net effect on grid balance.

2.2.2. Materials and devices

A primary obstacle for air-source heat pumps in cold climates is frost accumulation on the outer part of heat exchanger. This frost layer insulates the fins, drastically reducing system efficiency and forcing more frequent and more energy-intensive defrost cycles. The search for a solution often turns to materials science, specifically developing surface coatings that prevent or delay frost formation [14]. The energy penalty and operational inefficiencies caused by defrosting remain a major drawback. They said that current designs endure a fundamental trade-off: the need for high heat-transfer surfaces makes them prone to frosting, and the defrost process itself introduces cyclic mechanical stresses that can compromise the longevity of the heat exchanger's materials. Thus, they are developing durable superhydrophobic and hygroscopic coatings that prevent water droplets from freezing or cause frost to form in a porous, less insulating manner that is easier to remove [14].

The inverters that enable the variable-speed operation of modern heat pumps also rely on power semiconductors. While new wide-bandgap materials like SiC (Silicon Carbide) promise greater efficiency, they introduce device-level challenges [15]. In SiC-based inverters research, it proves their potential for significant energy savings in heat pump applications. However, their analysis also

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implies that realizing these gains requires managing the higher cost of the semiconductors themselves and overcoming associated engineering hurdles like managing electromagnetic interference and ensuring powerful thermal management to deal with heat density, all of these will impact the final system's cost and reliability. As the adoption of electric vehicles and renewable energy surges, however, the production yield of SiC and GaN (Gallium nitride) devices is increasing dramatically. This competition and improved manufacturing yields are steadily driving down costs, making them more viable for heat pumps.

The effectiveness of any heating system is dictated by the building envelope. For electrification to be truly efficient, existing homes often require deep energy retrofits with high-performance insulation [16]. As explored in this article, materials like Vacuum Insulation Panels (VIPs) offer a compelling solution due to their exceptional thermal resistance per unit thickness [16]. Nonetheless, their widespread use is precluded by high cost, concerns over long-term durability, and the risk of catastrophic performance loss when the vacuum seal is damaged. This results contractors with bulkier, more conventional materials that can be impractical to install in remolding without major structural modifications, presenting a significant materials-based barrier to reducing heating loads.

2.3. Results & discussion

2.3.1. Small cars

Table 1. The cathode materials with their corresponding specific energy [6]

Cathode Material	Midpoint voltage vs. Li (C/20)	Specific Capacity (Ah/kg)
LCO	3.9	155
LMO	4.0	100-120
NCA	3.7	180
NMC	3.8	160
LFP	3.4	160

Table 1 illustrates the value of cathode materials' specific energy and their midpoint voltage vs. Li (C/20). LCO is $LiCoO_2$, LMO is $LiMn_2O_4$, NCA is $LiNi0.8Co0.15O_2$, NMC is LiNIxMnyCo1-x-yO2, and LFP is LiFePO4 [6]. The midpoint voltage vs. Li (C/20) refers to the average voltage at which the battery operates, contributing to the essential factor in the batteries power and energy density. The higher voltage it is, the more energy per electron moved. Specific capacity refers the energy per unit mass, also referring how much energy storage the material offers for its weight. In this table, the Ah/kg refers the electric energy stored in the batteries (Ah=Q, where Q is the symbol of charge) per unit kilogram.

However, the specific energy can be obtained by multiplying the midpoint voltage to the specific capacity (Specific Energy = Midpoint Voltage (V) × Specific Capacity (C/kg)). Thus, it would conclude that NCA (666 J/kg) offers the highest theoretical specific energy, followed by NMC (608 J/kg) and LCO (604.5 J/kg). LMO (400-480 J/kg) has the lowest specific energy among the group. Therefore, NCA, NMC and LCO can be used in consumer electronics (mobile phones, laptops), long-range electric vehicles (EVs), drones and from those where maximizing runtime or range is critical. LMO has the highest voltage and the lowest specific capacity. Thus, it is suitable to apply in some power tools and medical devices. For LFP, it usually applied in EVs where cost and safety are priorities, electric buses and grid energy storage systems.

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2.3.2. Residential heating

Table 2. Performance of defrosting for three surface categories [14]

	Bare surface	Hydrophilic surface	Superhydrophobic surface
Melting time (s)	147	128	107
Energy consumptions (kJ)	301.7	258.8	244.7
Retained water mass (kg)	0.076	0.074	0.039
Frost thickness (mm) (For 20 min)	0.82	0.75	0.68
Frost mass (kg) (For 80 min)	0.302	0.267	0.215
Total heat transfer (kJ)	2437.7	2667.9	3047.2

Table 2 displays the comparison of the melting time in second, energy consumptions in kJ, retained water mass in kg (amount of water after the frost melted), frost thickness in 20 min and 80 min respectively and total heat transfer measured in kJ (total amount of heat exchanged during the operation, indicating the thermal efficiency of the system) for three different surfaces categories. Firstly, superhydrophobic surface has the shortest melting time (107s) and the lowest energy consumption (244.7 kJ). Thus, it is the best surface type of draining. As ice melts, the water beads up and rolls off (due to the high contact angle), exposing more of the cold surface directly to the warm defrosting air. This makes the heat transfer during defrosting more effective.

Retained water mass is also a critical measurement for performance of defrosting as the leftover water can refreeze again instantly, resulting faster frost regrowth and requiring more frequent, demanding defrost cycles. The superhydrophobic surface's ability to minimize retained water directly breaks this cycle to achieve long-term energy savings. Therefore, superhydrophobic surface retains less than half the water (0.039 kg) of the other surfaces. The thickness after 20 minutes and the mass formed after 80 minutes are both the lowest on the superhydrophobic surface. This is because its water-repelling nature makes it difficult for water vapor in the air to form a stable frost layer. For total heat transfer perspective which is the most essential part of the performance of defrosting, the superhydrophobic surface has the highest total heat transfer (3047.2 kJ). This is because by drastically reducing the insulating frost layer and maintaining low airflow resistance, the surface allows the heat exchanger to operate at peak efficiency for a much longer portion of the cycle. The other surfaces are hampered by their thick frost layers, which act as a barrier to efficient heat transfer.

3. Conclusion

This paper describes the limitations of electrification on small cars and residential heating and its corresponding solution. Electrification of small cars and residential heating provides a way of increasing efficiency and significant emissions reductions.

Electrification improves where renewable energy powers the technologies. Battery-electric vehicles (BEVs) are substantially more efficient than internal combustion engines and heat pumps provide more heat per unit of electricity than fossil fuel boilers. This shift can promote a deep decarbonisation when supported by a clean grid.

However, electrification is impeded due to material constraints and integration issues. For small cars, battery technology faces a critical equilibrium point between energy density, fast-charging capability, and cycle life. Material science barriers, such as low ions' movement ability in cathodes

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and lithium dendrite growth, limit performance and necessitate advanced, costly materials like silicon carbide for power electronics. For residential heating, air-source heat pumps lose efficiency in cold weather condition due to frosting, requiring advanced surface coatings. Furthermore, the effectiveness of electrification depends on improving building insulation effect and managing the high initial investment cost.

Finally, maximizing the benefits of electrification require the entirety approaches. This includes modernizing the grid, implementing smart charging and dispatching strategies (like using heat pumps as a virtual power plant), developing seasonal thermal energy storage and advancing material science to overcome current limitations. The environmental payoff is only assured through the synergistic decarbonisation of both terminal technologies and the electricity grid itself.

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