



ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT
CENTER FOR RENEWABLE ENERGY TECHNOLOGY

**IMPACT OF ELECTRIC VEHICLE EVOLUTION ON ENERGY SYSTEM
AND ITS EMISSION REDUCTION**

A thesis submitted to the school of graduate studies of Addis Ababa University, College of Technology and Built Environment in partial fulfillment for the Degree of Masters of Science in Renewable Energy Technology

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Addis Ababa, Ethiopia

APPROVAL PAGE

I hereby certify that I have read and evaluated this report entitled on “Impact of Electric Vehicle Evolution on Energy System and Its Emission Reduction” prepared under my guidance by Abdulaziz Nuredin. Hence, I endorse that it is submitted as fulfillment of the requirement for the Masters of Science in Renewable Energy Technology.

.....

Advisor’s Name

.....

Signature

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Date

DECLARATION

I, Abdulaziz Nuredin, hereby declare that this thesis entitled “Impact of Electric Vehicle Evolution on Energy System and Its Emission Reduction” is the result of my own work. All source and material used for this thesis have been properly acknowledged. This thesis is submitted in partial fulfillment of the requirement for Master's science in Renewable Energy Technology at Addis Ababa University and to make available at the university's library under its rule and regulation. I further declare that this thesis has not been submitted to any other institutions for the reward of any academic degree, diploma, or certificate.

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ABSTRACT

Ethiopia has adopted ambitious electric mobility policies, including fiscal incentives for electric vehicles (EVs) and a ban on the import of internal combustion engine (ICE) vehicles. While these measures position transport electrification as a central pillar of the country's Climate-Resilient Green Economy strategy, their long-term implications for electricity demand, power system investment, emissions mitigation, and economy performance remain insufficiently quantified. Existing studies largely assess transport electrification on grid stress and limited long term energy planning, EVs transition emission mitigation separately from national climate commitment targets, assuming homogeneous vehicles in transport energy modelling, and limited integration of transport demand growth with EVs diffusion. This study address this gaps by developing one of first Ethiopian-specific integrated transport-energy system model to evaluate impact of electric vehicle (EV) evolution on energy system from 2025 to 2050. Its novelty lies in embedding EV diffusion within fleet growth, power system expansion, and climate mitigation objective within unified analytical framework, to assess energy, environmental, investment and economic outcomes.

The analysis combines transport demand growth with a Gompertz-based vehicle ownership model, policy-based logistic EVs diffusion model, and the Open Source Energy Modeling System (OSeMOSYS) to represent electricity demand for heterogeneous vehicle segment, technology-specific energy consumption and GHG emission, and long-term power system expansion. Three EVs adoption scenarios are examined in addition to businesses as usual (BAU): Moderate Transition, Ambitious National Target and Net-Zero Mobility by embedding them within a baseline entire economy demand. A key assumption underpinning the analysis is that transport demand continue to expand under rapid population growth and urbanizations, requiring de-carbonization to occur alongside with the increasing mobility rather than through demand saturation.

The results indicates that in ambitious and net-zero scenarios transport electrification reduces transport energy demand and emission substantially with larger economic outcome, despite the rapidly increasing electricity demand after 2035. Under net-zero electrification cumulative energy saving reaches 239TWh, while demanding additional capacity expansion of 25GW from the baseline case of 150 GW for entire economy by 2050, whereas the baseline case emission declined by 65%. Even though significant emission mitigation is observed with rate of EVs adoption in all scenarios, with 95% electricity supply from renewables, transport electrification alone is insufficient to meet national NDC target by 2035. The economic return in net-zero scenario saves \$44 billion through reduced fuel imported and lower EVs maintenance costs, which can partially offsets the investment requirement for electricity generation of \$64 billion by 2050. The findings indicate that transport electrification represents a strategic pathway for enhancing energy security, reducing fuel import dependence, and advancing Ethiopia's long-term climate goal.

The results provide a quantitative evidence base for policymakers in setting realistic EV adoption targets, aligning transport policies with power sector expansion plans, and prioritizing investments in electricity generation and charging infrastructure. The analysis highlights that achieving national climate objectives requires coordinated action across the transport, energy, industry, and land-use sectors. These insights can support policymakers in designing integrated, cost-effective, and climate-aligned development strategies that maximize the economic and environmental benefits of Ethiopia's electric mobility transition.

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Table of Contents

APPROVAL PAGE	ii
DECLARATION	iii
ABSTRACT	v
ACKNOWLEDGMENT	vi
Table of Contents	vii
LIST OF ACRONYMS	ix
LIST OF TABLES	1
LIST OF FIGURES	2
CHAPTER ONE	3
1. INTRODUCTION	3
1.1 Background	3
1.2 Problem of Statement	4
1.3 Research questions	5
1.4 Objective	6
1.4.1 Specific Objective	6
1.5 Significance of Study	6
1.6 Scope	7
CHAPTER TWO	8
2. LITERATURE REVIEW	8
2.1 Road Transport Fleet Growth and Energy Demand	8
2.2 Transport Electrification and Evolusion of Electric Vehicle	10
2.3 EV Charging Demand and Electricity System Implications	11
2.4 Inegrated Transport-Energy System Modelling	13
2.5 Transport Electrification and Climate Mitigation	13
2.6 EV Charcterstics	14
2.6.1 Accommodation of charging circuit	15
2.7 Integrating Transport Electrification with Renewable Source	17
2.8 Overview of Ethiopian Power Sector	17
2.8.1 Electricity Demand and Supply Mix	18
2.9 Research Gap Synthesis	19
2.10 Policy Assessment	20
CHAPTER THREE	22

3	METHODOLOGY	22
3.1	Material and Methods	22
3.1.1	Materials	22
3.2	Data Sources and Fleet Characterization	23
3.2.1	Data quality and Availability	25
3.3	Analytical Framework and Designing Models	25
3.3.1	Vehicle Ownership and Fleet Evolution Modeling	26
3.3.2	EV Transition Modeling	27
3.3.3	Transport Energy Demand Modelling	28
3.3.4	EV Adoption Scenarios	29
3.3.5	GHG Emission Reduction Analysis	31
3.3.6	Economic and Energy Saving Assessment	32
3.3.7	Model Calibration and Simulation	34
3.3.8	Model Validation and Verification	34
3.3.9	Key Assumptions Rationale	36
	CHAPTER FOUR	37
4.	RESULT AND DISCUSSION	37
4.1	Result	37
4.1.1	Transport Demand growth	37
4.1.2	Energy Demand and Investment Required	39
4.1.3	Emission Mitigation	44
4.1.4	Economy and Energy Saved	45
4.2	Integrated Result Discussion	49
4.3	Key Findings	52
4.4	Study Limitation and Future Research	54
	CHAPTER FIVE	55
5.	CONCLUSION AND RECOMMENDATION	55
5.1	Conclusion	55
5.2	Recommendation	57
	Annexes	59
	Annex I. Road transport fleet dynamics	59
	Annex II. Energy and related data	60
	Annex III. Summary of Assumptions	60
	References	61

LIST OF ACRONYMS

BAU: Business-As- Usual

EV: Electric vehicle

GDP: Gross domestic product

GHG: Greenhouse gas

GW: Giga watt

ICE: Internal combustion engine

IPCC: Intergovernmental panel on climate change

IEA: International energy agency

IRENA: international renewable energy agency

MoTL: Ministry of Transport and Logistics

Mt: Million ton

MYC: motor cycle

NDC: Nationally Determined Contribution

OSeMOSYS: Open Source Energy Modeling System

TWh: terra watt hour

USD: united States dollar

VRES: variable renewable energy sources

LIST OF TABLES

Table 1 : Popular commercially available EV in Addis Ababa	16
Table 2: Road transport fleet and activity data in Ethiopia 2024/2025.....	59
Table 3: Ethiopian energy resources and related data used in thus study	60

LIST OF FIGURES

Figure 1: Source: - MoEW- Strategy for Water and Energy (CRGE)	19
Figure 2: Power Generation, ...	19
Figure 3: Road transport fleet in 2024/2025	24
Figure 4: schematic process of the methodology followed in this study	26
Figure 5: Vehicle ownership growth.....	37
Figure 6: Vehicle demand growth and transition to EV	38
Figure 7: EV share growth.....	39
Figure 8: Capacity expansion for EV Adoption pathways.....	41
Figure 9: Energy production by technology for EV Adoption pathways	42
Figure 10: Investment required by technology type	43
Figure 11: Annualized investment costs for electricity generation mix.....	44
Figure 12: Cumulative emission across scenarios.	45
Figure 13: Transport energy consumption across Scenarios.....	46
Figure 14: Energy saved across scenarios.....	47
Figure 15: Operation costs across scenarios	48
Figure 16: Transport operational cost saving across scenarios	48

CHAPTER ONE

1. INTRODUCTION

1.1 Background

The transport sector plays a critical role in the Ethiopian economy, contributing about 10–12% of gross domestic product (GDP) during the 2019–2023 fiscal years [1], [2]. Passenger transport demand is projected to increase significantly due to rapid population growth, accelerating urbanization, and growing per capita income; as a result total passenger travel is expected to rise from 40 billion passenger-kilometers in 2010 to 220 billion passenger-kilometers by 2030, which elevates the corresponding transport-sector emissions from 2.5 Mt CO₂e to 13.1 Mt CO₂e over the same period [3].

In response to growing concerns over greenhouse gas (GHG) emissions, fuel import dependency, and climate issue, governments and academic community paying more attentions to electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs) as a central pathway for decarbonizing road transport. When powered by renewable based electricity, EVs can significantly reduce transport sector emissions while generating co-benefits such as improved air quality, reduced fuel imports, and lower operating costs [4], [5].

The climate mitigation potential of EVs is strongly influenced by the electricity supply mix. Integrating transport electrification with a renewable-dominated power sector enhances emissions reductions, and improves overall system efficiency, particularly in systems with high shares of variable renewable energy such as wind and solar. To overcome the barriers that diminishes adoption of EV such as widespread electrification, ranging from vehicle technology and battery costs to charging availability to consumer preferences and awareness requires additional public and private initiatives [4]. Consequently, coordinated planning between transport electrification and power system expansion is essential to ensure that rising electricity demand from EV adoption is met reliably and sustainably.

The Government of Ethiopia has articulated ambitious climate mitigation targets under its revised Nationally Determined Contribution (NDC 3.0). By 2035, the country aims to reduce greenhouse gas emissions to approximately 141 Mt CO₂e equivalent to about a 41% reduction relative to the

business-as-usual (BAU) trajectory through unconditional domestic efforts, and further to around 71 Mt CO_{2e} under the conditional pathway, representing an estimated 71% reduction below BAU levels by 2035 [6]. Under the former NDC, the transport sector alone was expected to contribute an emission reduction of about 10 MtCO_{2e} relative to BAU emissions by 2030 [7], [8], [9].

In support of these objectives, the government initially targeted the deployment of 4,800 electric buses and 148,000 electric passenger vehicles by 2030. These targets were effectively met within two years following the introduction of comprehensive fiscal incentives in 2022, including reducing import duties, exempting value-added tax, excise tax, and surtaxes. As a result, electric vehicle (EV) adoption trajectories have been substantially revised upward, with national targets increasing to approximately 500,000 EVs.

Building on this momentum, the government has set a further high-ambition objective to transition 85% of road passenger internal combustion engine (ICE) vehicles to electric vehicles by 2040 [9], positioning transport electrification as a central pillar of Ethiopia's long-term low-emission development strategy.

Thus, this rapid evolution of EV uptake likely to introduces new challenges for the national energy system. Large scale electrification of road transport is expected to increase electricity demand and influence long-term generation capacity requirements and investment needs [5]. Understanding how different EV evolution pathways affect electricity demand growth, generation mix expansion, and emissions trajectories is therefore essential for ensuring a cost-effective and climate-aligned energy transition.

1.2 Problem of Statement

Mitigating climate change requires a transition from fossil fuel-dependent transport systems to low-emission alternatives. Electric vehicles (EVs) are increasingly recognized as a key decarbonization option due to their potential to reduce greenhouse gas emissions, improve energy efficiency, and reduce dependence on imported petroleum fuels. The road fleet in Ethiopia is expanding driven by population growth and urbanization. Transport sector is a major consumer of imported petroleum fuels presenting significant pressure on foreign currency reserves and a growing source of GHG emissions.

Accordingly, Ethiopia has adopted ambitious electric mobility policies, including restrictions on internal combustion engine (ICE) vehicle imports and a target of achieving 85% EV penetration

in the road transport fleet by 2040 [9]. However, to achieve such large-scale EV adoption targets, it will substantially increase electricity demand and require corresponding investments in power generation, infrastructure expansion, and long-term energy system planning.

Despite these policy commitments, the long-term implications of large-scale transport electrification for Ethiopia's energy system remains not quantified. Existing studies primarily focus on vehicle adoption trends, transport sector emissions, or short-term electricity impacts in isolation. At the national level, no integrated transport–energy system modelling study has comprehensively assessed long-term EV adoption within transport demand growth, electricity supply expansion for EVs induced charging demand, and EVs emission mitigation interaction with climate objectives over the long term.

Consequently, lack of integrated assessment evidence creates uncertainty in planning alignments regarding the magnitude and timing of EV-induced electricity demand, the associated power system investment requirements, the achievable emission mitigation, and the overall economic outcomes of the transition. Without integrated long-term energy system planning, the rapid growth of EV-related electricity demand may place additional pressure on generation expansion and increase investment requirements. Moreover, the knowledge gap on the timing and scale of future electricity demand could undermine the long-term viability of transport electrification, weaken coordination between transport and energy sector strategies, and delay progress toward national climate mitigation objectives.

Therefore, comprehensive and integrated assessment of EV adoption pathways and their implications for electricity demand, power system expansion, emissions mitigation, investment requirements, energy saving efficiency and economic outcome is essential to support evidence-based transport electrification policies and integrated energy planning in Ethiopia.

1.3 Research questions

Despite Ethiopia's ambitious transport electrification policies, there remains limited understanding of how such large scale EV adoption will influence future transport energy demand, electricity requirements, power system expansion, emissions mitigation, and economic performance. As a result, important questions remain regarding the scale of electricity demand growth, the magnitude

of infrastructure investments required, the achievable environmental benefits, and the extent to which transport electrification can contribute to national climate objectives.

To address these knowledge gaps and support evidence-based transport and energy planning alignment, this study seeks to answer the following research questions:

1. How do vehicle fleet growth and EV adoption alter transport energy demand and electricity requirements over time?
2. What magnitude of energy savings, economic benefits and greenhouse gas emission reductions can be achieved under alternative EV adoption pathways?
3. How does EV-induced electricity demand influence long-term power generation capacity expansion and investment requirements?
4. To what extent do national EV adoption target and alternative adoption pathways support climate commitments (NDC) targets?

1.4 Objective

The Objective of this study is to assess the impact of electric vehicle (EV) evolution on energy system and its emission reduction from transport sector onward to 2050

1.4.1 Specific Objective

The specific objective of this study are to:

1. Quantify electricity demand for EV adoption across pathways vehicle segments
2. Quantify energy saving and emission reduction under alternative EV adoption pathways
3. Assess how EV adoption influences long-term capacity expansion and investment needs
4. Assess the contribution of national EV policy to achieve NDC targets and long term complete e-mobility goal.

1.5 Significance of Study

Transport electrification is a key component of Ethiopia's Climate-Resilient Green Economy strategy, yet its long-term implications for electricity demand, power system expansion, investment requirements, and emissions mitigation remain insufficiently understood. This study addresses this gap by developing one of the first integrated transport–energy system models for Ethiopia, linking transport demand growth, EV adoption pathways, electricity generation planning, emissions mitigation, and economic outcomes.

The findings provide quantitative evidence on the scale and timing of electricity demand growth, generation capacity expansion, investment needs, and potential energy, economic, and environmental benefits of transport electrification. These insights support evidence-based policymaking and facilitate the alignment of transport electrification targets with national energy planning, climate commitments, and sustainable development objectives.

1.6 Scope

The study encompasses analysis of transport demand growth and the associated energy demand from 2024 onward to 2050, driven by population growth and urbanization. It also includes assessment of impact electric vehicle evolution on Ethiopia's energy system and the corresponding emission mitigation. The study incorporate evaluation of plausible alternative EV adoption pathways, and associated economic outcome from energy saving and operational cost. The study does not address distribution- level grid constraint and development of charging infrastructure.

CHAPTER TWO

2. LITERATURE REVIEW

The transport sector plays a critical role in economic development by enabling mobility for people and goods, supporting agriculture, industry, trade, tourism, and access to social services. It makes education, health and other infrastructures more accessible to the public. It plays a significant role in facilitating the movement of the society [10]. This literature review aims to explore existing transport electrification studies globally and in Ethiopia and to support the objective of this study.

2.1 Road Transport Fleet Growth and Energy Demand

Road transport systems comprise diverse vehicle categories that differ substantially in operational characteristics, energy consumption patterns, vehicle utilization rates, and emission intensities [11], [12]. Passenger cars, sport utility vehicles (SUVs), minibuses, buses, light-duty commercial vehicles, and heavy-duty freight trucks each contribute differently to total transport energy demand despite often representing different proportions of the vehicle fleet [13]. Vehicle categories exhibit considerable variation in annual mileage, occupancy rates, payload requirements, and energy intensities [11].

Given these considerations, this study represents the transport sector using disaggregated vehicle categories with technology-specific energy consumption, activity levels, and emission characteristics. This approach improves the accuracy of future transport energy demand projections and enables more realistic estimation of EV electricity requirements and emission reduction potentials under alternative adoption pathways [14], [15].

Furthermore, transition toward transport electrification amplifies the importance of fleet heterogeneity because electrification potential differs considerably across vehicle segments [15]. Passenger cars typically electrified faster due to lower battery requirements and greater market maturity, whereas heavy-duty freight vehicles face additional technological and infrastructure challenges [16].

Road transport demand is closely linked to socioeconomic development and is primarily driven by population growth, urbanization, industrialization, and rising income levels [17]. As economies develop, increased household income improves vehicle affordability, leading to higher motorization rates and greater demand for mobility services [18]. Consequently, long-term

transport energy demand is largely determined by vehicle fleet growth and travel activity patterns [19].

Numerous studies have demonstrated a strong relationship between GDP per capita and vehicle ownership growth [20]. Vehicle ownership generally follows a non-linear growth trajectory characterized by slow growth during early economic development, accelerated expansion during industrialization, and eventual saturation at higher income levels [17]. To capture this behavior, researchers have widely employed Gompertz and logistic growth functions in vehicle ownership forecasting studies [19], [21].

The Gompertz model has become one of the most widely adopted approaches because it explicitly represents the S-shaped relationship between economic development and motorization while accounting for market saturation effects ([17] [19]. Previous applications in China, India, Latin America, and other emerging economies have demonstrated the model's ability to provide robust long-term projections of vehicle ownership under varying economic growth conditions [19]. Gompertz-based vehicle ownership model approach captures the dynamic relationship between income growth and motorization while representing long-term saturation behavior, thereby providing a consistent basis for EV diffusion and energy system assessment ([17] [19].

In Sub-Saharan Africa, rapid population growth, urbanization, and economic expansion are expected to drive significant increases in future transport demand (IEA, 2024). According to World Bank development indicator in 20204 Ethiopia is expected to experience a similar trend as economic development and urban mobility requirements continue to grow. The vehicles segment engaged in public transport services in Ethiopian road transport supply are cars, mini & full-sized buses, and two & three-wheeler. Ministry of Transport and Logistics (MoTL) confirmed that there were 1.5 million fuel-powered vehicles, and over 100,000 electric vehicles in Ethiopia in 2023 [22].

The road transport in Ethiopia dominates passenger and freight movement and is therefore a major driver of energy consumption and greenhouse gas (GHG) emissions. Rapid population growth and urbanization are projected to substantially increase travel demand, leading to a sharp rise in sectoral energy use and emissions if conventional internal combustion engine (ICE) vehicles remain dominant. The transport fleet is composed of a variety of vehicle classes, and empirical studies on Ethiopian road transport shows that heavy-duty vehicles, despite smaller fleet shares,

consume larger amounts of energy and contribute significant amount of emissions. On the other hand light-duty vehicles dominates vehicle numbers but have lower per-vehicle energy consumption [22].

Transport energy consumption is influenced not only by total vehicle ownership but also by fleet composition and vehicle usage characteristics. Accurate representation of fleet heterogeneity is essential for realistic energy system modeling. Several studies demonstrate that aggregated or homogeneous fleet representations, which can significantly misestimate energy demand and emissions. Understanding future fleet growth and composition is essential for assessing transport energy demand, electricity requirements, emissions, and infrastructure needs associated with transport electrification [23]. Since energy consumption per kilometer and charging requirements vary substantially among vehicle classes, leading to different implications for future electricity demand [24].

Passenger vehicles generally dominate fleet numbers, whereas freight trucks and buses often account for a larger share of total transport energy consumption due to their higher utilization rates and fuel requirements [12]. Therefore, aggregating all vehicle classes into a single representative category can lead to significant errors in estimating energy demand and emissions [25]. Several studies have demonstrated that disaggregated fleet representations provide more realistic estimates of transport energy consumption, emission trajectories, and technology adoption pathways than aggregate approaches ([11], [26]. Accordingly, explicit representation of heterogeneous vehicle categories has become increasingly common in long-term transport energy models and decarbonization assessments [15].

2.2 Transport Electrification and Evolusion of Electric Vehicle

Transport electrification is emerging as one of the most promising strategies for reducing fossil fuel dependency, improving energy security mitigating greenhouse gas emissions from transport sector, which remains dominated by fossil fuel use[23][25] [27][28]. Electric vehicles (EVs) convert electrical energy to mechanical energy more efficiently than internal combustion engine vehicles and no direct exhaust emissions. Transport electrification reduce energy consumption and associated emissions when the electricity supply is from low carbon or renewable power generation [29], [30] [31].

Well-to-wheel and system-level assessments shows that the emission reduction potential of EVs depends strongly on the carbon intensity of the electricity supply mix [32]. In electricity systems with high fossil fuel shares, EV deployment leads to limited net emission reductions because emissions are displaced rather than avoided. In contrast, low-carbon and renewable-dominated electricity systems enable substantial reductions in total transport-related emissions [30]. Governments world wide hve increasingly adopted policies aimed at accelerating EV deployment through financial incetive, tax exemptions, charging infrastructure investement, and ristrictions on ICE vehicles [16].

Adoption of new technologies generally follows a diffusion process, characterizing by slow intial uptake, accelerated market penetration and, and entual saturation [33],[34].This pattern is usuaully represented using logistic and bass difussion models, both of which have neen extensively applied in technology adoption forecasting [34][35]. In context of transport electrification, EV adoption is infulenced by multiple interacting factor, including vehile cost, fuel price charging infrastructre availability, consumer prefrences, technologi maturity, and governemnet policy interventions[15].

Recent litrature suggests that EV pnetration should be modeled as a technolgy substitution process embeded within overall fleet growth rather than as an independent growth trajectory [16][36]. This approach refelect the reality that EV adoption occurs throgh gradual replacement of conventional vehicles within the expanding transport system. Ignoring the interaction between fleet growth and EV diffusion can results in unrealistic projection of veehicl stock, electricity demand and emission mitigations. In developing economies, policy measures often play a dominant role in accelerating EV adoption due to relatively immature markets and infrastructure constraints [15]. Ethiopia's transport electrification strategy, which combines fiscal incentives with restrictions on ICE vehicle imports, represents a policy-driven transition pathway that is expected to significantly influence future fleet composition [37].

2.3 EV Charging Demand and Electricity System Implications

Electrification of road transport yields uneven electricity demand growth across vehicle segments, underscoring the need for disaggregated modeling[38]. Consideration of heterogeneous vehicle usage patterns show that no single propulsion technology is optimal across all driving profiles and electricity supply conditions.

The interaction between transport electrification and electricity systems is particularly important in developing countries experiencing rapid economic growth and rising electricity consumption [39]. Under such conditions, EV-induced electricity demand adds to existing demand growth from industrialization, urbanization, and population expansion[15]. Consequently, transport electrification cannot be assessed independently of broader energy system development.

The magnitude of electricity for EVs charging demand depends on vehicle stock growth, travel activity, vehicle efficiency, battery characteristics, and charging behaviour[15], [40]. Large-scale EV adoption introduces a new, growing electricity demand that must be accommodated through long-term generation capacity expansion and investment planning. Consequently, understanding and forecasting EV adoption induced electricity demand is essential for integrated national energy system and network planning [29].

Worldwide EV charging is projected to grow about 6–8% of total electricity demand by 2035, up from less than 1% today. While such charging demand growth would present operational challenges at the local grid level, at the national scale it primarily raises questions of generation adequacy, capacity expansion timing, and investment requirements [41], [42].

In early stages of EV adoption the impact of EVs on electricity systems is limited; however, high-penetration scenarios indicate a measurable increase in electricity demand over the long term. EV charging projections for Europe with considerable variation across countries suggested to reach approximately 9–10% of total electricity consumption by 2050 under high electrification assumptions[43].

The study consistently identifies temporal charging patterns (concentration of load) as the main challenge associated with EV-related electricity demand [44], [45], [46]. Empirical studies based on real charging data show that EV charging demand exhibits strong daily (during evening hours), weekly [47][48], and seasonal variability, which coincides with existing system peaks

Several studies have demonstrated that long-term planning frameworks are required to evaluate how EV adoption influences future electricity demand, generation expansion, and infrastructure investment requirements [49],[40]. Integrating EV charging demand within national energy planning therefore provides a more realistic basis for assessing future power system needs. The increasing interdependence between transport electrification and electricity systems has

highlighted the importance of integrated modelling approaches capable of representing cross-sector interactions [39].

2.4 Integrated Transport-Energy System Modelling

The Increasing interdependency between transport electrification and electricity system has highlighted the need for integrated approaches capable of capturing cross-sectoral interactions and long-term infrastructure planning [50],[51]. Traditional models typically focus on vehicle ownership, travel demand, or technology adoption without explicitly representing electricity supply implications, while energy system models often treat transport demand as exogenous input[51]. Such separation can limit the ability to assess how transport electrification influences electricity demand growth, generation capacity expansion, investment requirement, and emission mitigation simultaneously [52][53].

To address the limitation, integrated transport-energy system models have been increasingly adopted to represent transport demand, technology transition, energy system, emission, and investment decisions within a unified analytical framework [50]. These models enable the evaluation of long-term energy pathways, technology deployment strategies, energy security implications, and climate mitigation outcomes under alternative policy scenarios[51] [53]

Accordingly, this study estimates EV electricity demand using vehicle-specific energy consumption and projected transport activity. The resulting demand is integrated into a national energy system optimization framework to evaluate implications for electricity generation capacity expansion and investment requirements.

2.5 Transport Electrification and Climate Mitigation

Transport sector accounts approximately one-quarter of global energy related carbon dioxide emissions and remains one of the most challenging sectors to decarbonize[15] [25]. Consequently, transport electrification has become a central component of international climate mitigation strategies [12],[29]. Electric vehicles can significantly reduce transport-sector emissions because electric drivetrains are considerably more energy efficient than internal combustion engine technologies [15]. Mixed fleets composed of battery electric vehicles, plug-in hybrids, hydrogen, and even compressed natural gas (CNG) electrified powertrains can achieve lower

overall emissions than uniform technology scenarios, particularly during periods of transition in the electricity system [28] [30].

However, the magnitude of emission reductions depends on both EV adoption levels and the carbon intensity of electricity generation[25]. The renewable-dominated power supply systems enables to achieve substantially greater climate benefits from transport electrification in contrary to fossil-fuel-based electricity generation. Studies have emphasized the importance of evaluating transport electrification within the broader context of power sector decarbonization [12]. Failure to account for electricity generation emissions may overestimate the climate benefits of EV deployment[25].

Analysis of vehicle emissions reveals a distinct pattern: heavier vehicles like coaches, buses, and trucks contribute the major road transport emission, about 28.44gm of carbon dioxide (CO₂) per vehicle and consume a larger energy up to 8946.37mg of fuel equivalent. Conversely, lighter vehicles (cars and minibuses) shows fewer emission up to 6.5g of CO₂ and consume lower energy ~2000mg fuel equivalent. However, for carbon monoxide (CO), this trend is reversed, with minibuses emitting the highest amount, about 420gm of (CO) and heavier vehicles emitting far less ~25-31gm (CO). Key determinants of growing transport emissions include traffic congestion, vehicle density, road characteristics, and the composition of vehicle types (old ICE) and EV shares. When the vehicle replaced by electric vehicles (EVs), energy consumption scales directly with vehicle size; truck trailers would require the most electrical energy (2.3 kWh) and cars least (0.15 kWh) per time step [54].

Ethiopia's electricity system is predominantly supplied by renewable energy resources, particularly hydropower, with increasing contributions from wind, solar, and geothermal technologies [55]. This renewable-rich generation mix creates favorable conditions for achieving substantial emission reductions through transport electrification. Nevertheless, the extent to which EV adoption contributes to national NDC targets [6] and long-term decarbonization goals remains uncertain. Therefore, integrated assessment approaches are increasingly used to evaluate transport and electricity sector transitions simultaneously.

2.6 EV Characteristics

The modern EV technologies are comparatively new, researches on EVs had focusing on increasing vehicle range and efficiency, reducing the price as well as developing methods for an

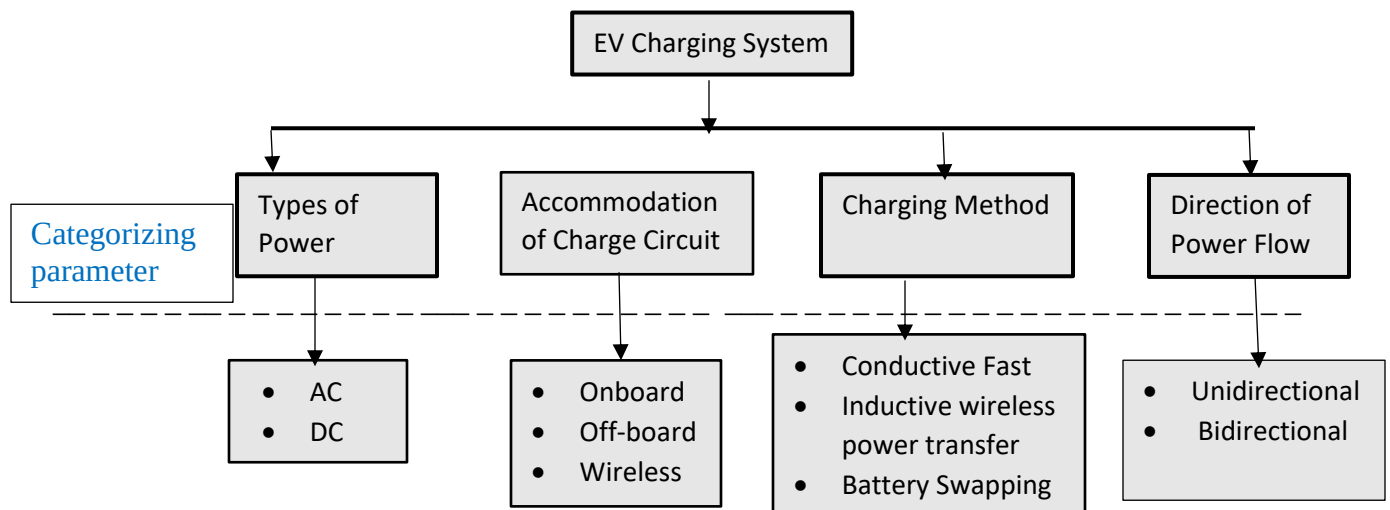
efficient charging system [56]. Modern EV charging systems use smart technologies and sophisticated power controllers to improve energy efficiency and streamline charging procedures [15]. EV charging uses either AC or DC power supplies. AC charging has different voltage and frequency levels based on the power system of a concerned country. In terms of the voltage levels, AC charging classified as Level I, II and III, where level III has the highest charging voltage [56]. Level I chargers are slow usually utilized at home (residential buildings), whilst private and public places include Level II, Level III, and Level IV chargers, corresponding to semi-rapid, rapid, and ultra-quick respectively [15].

2.6.1 Accommodation of charging circuit

There exists a diverse range of EV-charging mechanisms, such as conductive, inductive and battery swap [42]. EV charging circuit system could be either in a car (on-board charging) or in a charging station (off-board charging). Onboard charger are compact in size, lightweight and low in cost allows the EV owner to recharge their car batteries wherever power supply is available, but possesses low power delivery capacity to the EVs, which causes a longer charging time and affects the driver satisfaction [56]. Contrarily, off-board EV charger has less concern in weight and size and facilitates multiple charging modes including slow and fast charging schemes in the same infrastructure. However, setting up off-board chargers can be expensive due to the multiple charging schemes within a charging station [42], [56].

Battery swapping is also another technique of charging with low power loss and no waiting time to charge, and very efficient known by off board charging system.[42] Apart from on and off-board chargers, wireless charging is considered as a third type of charging system, in which the energizing coils are set up outside the vehicle, but the receiving coil and converter are mounted inside the vehicle. This charging method is convenient for power transfer between the charging stations and EVs; however, the power loss is high and low in efficiency [42], [56].

Contactless charging system typically uses wireless power transfer (WPT) technology to charge the battery. WPT system can operate in every voltage levels (Levels 1, 2 and 3) and has the power rating up to 20 KW. The recorded efficiency is up to 90%. Based on the charging technology, WPT can be divided into four types namely, resonant inductive, inductive, capacitive and low frequency permanent magnet coupling power transfer [56].



The characteristics of most popular EVs available in local markets and on road are shown in Table 1, characteristics are sourced manufactures sites [57].

Table 1 : Popular commercially available EV in Addis Ababa

Vehicle model / Manufacturer	Type	Peak power (kW)	Battery (kWh) usable	Range (km)	Top speed (km/h)	Charging time (0% – 80%) (hr)	
						L1 & L2	DCFC
BYD Atto 3 /BYD	BEV	150	60.5	345	160	15-8	0.8-0.4
BYD Dolphin/BYD	BEV	150	60.5	350	160	14- 8	0.8-0.4
MG ZS EV (Long Range) / MG Motor Ethiopia	BEV	130	72.6	~440	165	10- 6	1 -0.6
Hyundai Kona Electric (Long Range) / Hyundai	BEV	150	64.0	~390	167	9-6	0.9-0.4
Nissan Leaf (40 kWh) / Nissan	BEV	110	40	~300	144	6	0.5
Hyundai Ioniq (Marathon Motors)	BEV Car	~100	38.3	~274	NI	NA	0.6-0.4
Volkswagen ID.4 Pro / Performance	BEV	~150	77	512	160	15- 7	1-0.41
BYD Tang (Flagship) / BYD	BEV (large SUV)	380	108.8	~460	190	15-11	1.5-0.8
Golden Dragon electric bus	BEV (bus)	~175	311	~148	84	NA	4.4-2.9
Golden Dragon/ Minibus Belayneh Kindie	BEV	NI	NI	~350	NI	NA	0.66

2.7 Integrating Transport Electrification with Renewable Source

The climate mitigation potential of EVs depends critically on the electricity supply mix [29] [30][58]. In renewable-dominated systems, transport electrification can deliver immediate and substantial emission reductions [59]. Ethiopia's power system, characterized by a high share of hydropower and growing solar and wind capacity, is particularly well positioned to benefit from EV adoption [29] [60].

Aligning EV charging demand growth with renewable expansion can reduce fossil fuel dependence, improve energy security, and lower system costs [61],[62] ,[63]. High shares of variable renewable energy sources (VRES), particularly wind and solar, introduce flexibility requirements; aligning EV charging with peak cultivation of VRES potentially helps to flatten the national residual load curve for the grid flexibility issue [63]. At the national scale, this alignment can be achieved through coordinated generation capacity expansion rather than through localized grid interventions [63]. Energy system optimization models are therefore well-suited to evaluate how EV adoption influences future investment pathways [29][42].

The integration between electric vehicle deployment and the electricity supply mix is crucial in determining decarbonization outcomes [43]. Increasing EV penetration raises electricity demand and, in the absence of coordinated charging, may require substantial expansion of generation capacity, as shown in European system-level studies [43]. At the same time, the emissions performance of EVs improves as the electricity mix becomes less carbon-intensive, with threshold analyses indicating that battery electric vehicles dominate optimal fleet configurations once power-sector emissions fall below certain levels. In systems with high shares of variable renewable energy, EV charging demand can provide flexibility by shifting load toward periods of high renewable availability, thereby reducing renewable curtailment and improving the integration of wind and solar generation when coordinated charging strategies are applied [43] [59].

2.8 Overview of Ethiopian Power Sector

Ethiopia's electricity sector is experiencing strong growth; Ethiopia increased its generation capacity from 755 MW to 5,200 MW between 2008 and 2023. Ethiopian electric power (EEP) is constructing new power plants, substations and transmission lines to meet national electricity demand aiming to raise its production capacity to 17,056 MW by 2030 to attain electricity access

for 78% [60]. However, the Ethiopian Electric Power (EEP) company is facing power instability, due to the poor quality of communications between power plants and the control center [64].

2.8.1 Electricity Demand and Supply Mix

Ethiopia's electricity supply is almost entirely from hydropower, planned to meet anticipated electricity demand by scaling up renewable generation, particularly through the expansion of hydropower. Ministry of water and energy (MoWE) tentatively plans to increase power generation from 5,200 MW installed capacity in 2024 to 24,092 MW of available capacity¹ by 2030. Moreover, diversify the energy mix to reduce dependence on hydropower (in recognition of the vulnerability of hydropower to rainfall variability). This will enable Ethiopia to meet future domestic peak demand (estimated at 14,213 MW by 2030) and export additional electricity (coincident maximum demand estimated at 3,655MW by 2030) to provide a critical source of foreign exchange income and support regional integration [65]].

EEP is managing 22 power station; among them 16 are hydropower plant of which 12 of them are fully commissioned hydropower plants with a total installed capacity of 4820.2 MW in 2024. [31] Current power generation from wind power plants with capacities are, Adama II (153MW), Ashegoda (120 MW) and Adama I (51MW). Additionally Ayisha II have been partially completed and started operation with the capacity of 80 MW. The rest of power generation is from steam geothermal and biomass (waste) reserves) [60], [65].

¹ *Installed hydropower capacity is the theoretical maximum that the system can produce, in reality, the actual generation capacity is lower due to the seasonality of rainfall. 2030 figures are therefore based on the 'very dry' hydrological conditions modelled the Power Sector Expansion Masterplan Study, which uses the 3 driest years of the last 45 and therefore assumes a worst case generation scenario*

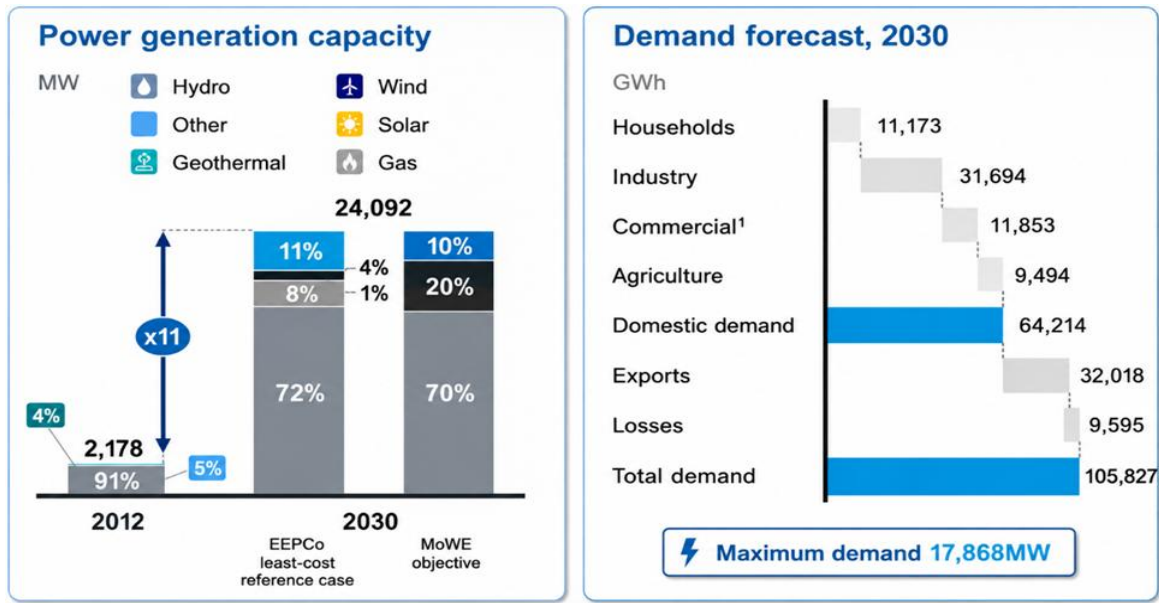


Figure 1: Source: - MoEW- Strategy for Water and Energy (CRGE) [65]

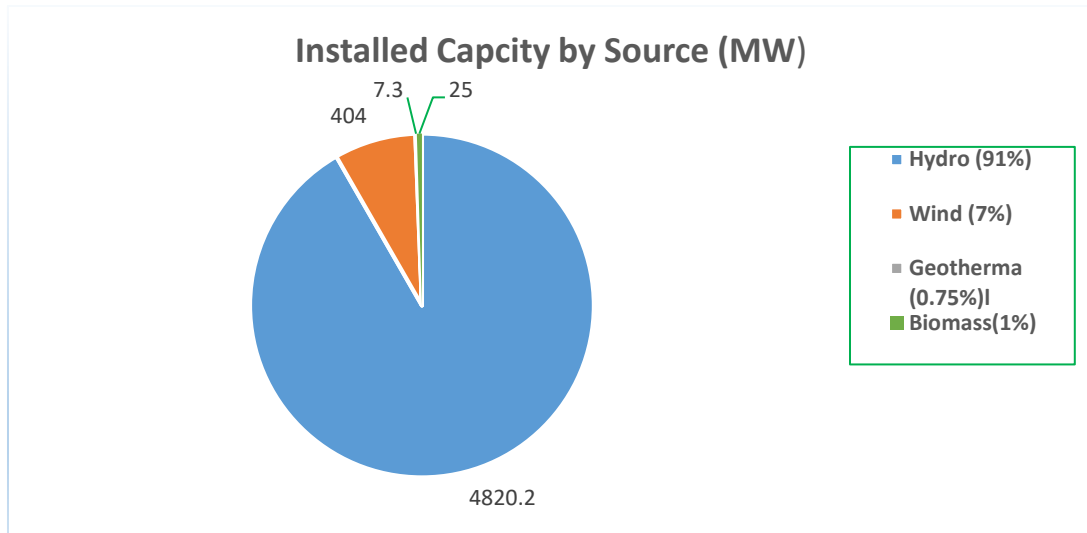


Figure 2: Power Generation, [66]

2.9 Research Gap Synthesis

Despite the extensive research on transport electrification, significant gaps remain in understanding its long-term implications for integrated energy system planning. Existing studies have predominantly focused on individual aspects of charging demand impact on the grid, vehicle adoption trends, and emission mitigation potential of EVs, often treating them as independent analytical problems. Consequently, the dynamic interaction between transport demand growth,

EVs adoption, electricity demand, power system expansion, and investment requirement remains insufficiently represented within a unified modelling framework.

Furthermore, many transport electrification studies rely on simplified representations of the vehicle fleet, assuming homogeneous vehicle characteristics and energy consumption patterns. Such approaches may overlook the heterogeneous nature of the vehicle segment, which significantly influences transport energy demand and electrification potential, charging requirements, and emission outcomes. EVs adoption is frequently modelled as an exogenous trend, rather than as a policy-based technology transition embedded within overall fleet growth and evolving mobility demand. This limits the ability to realistically assess future electricity requirements and infrastructure needs under large-scale transport electrification.

Although numerous studies quantify emission reduction associated with EVs adoption, there remains a limitation is the inadequate integration of transport electrification pathways with NDC targets and long-term climate mitigation objectives. These limitations are particularly evident in Ethiopia, where ambitious electric mobility policies have been introduced despite the absence of an integrated national-scale assessment linking transport electrification with long-term energy planning. To date, no study has systematically evaluated how alternative EV adoption pathways influence electricity demand growth, power generation expansion, emission reduction, and economic outcomes while assessing their contribution to national climate commitments.

This study adrees this gaps by developing one of the first Ethiopia-specific integrated transport-energy system models that combines transport demand expansion, policy-driven EV diffusion, electricity system expansion, climate mitigation, and economic assessment within a unified analytical framework.

2.10 Policy Assessment

Government of Ethiopia promotes transport electrification through policy as part of its Climate Resilient Green Economy (CRGE) strategy. Under Ethiopia's Nationally Determined Contribution (NDC) updated in 2021 sets to mitigate greenhouse gas (GHG) emissions by 64% relative to business-as-usual levels by 2030 ($\approx 255 \text{ MtCO}_2\text{e}$), with the transport sector explicitly identified as a priority mitigation area of (10 MtCO_2e) emission reduction [3] [67]. This commitment is reinforced through national planning instruments, including the Long-Term Low Emissions

Development Strategy (LT-LEDS, 2020) and the Ten-Year Development Plan (2021–2030), which recognize electric mobility as a key pathway to reduce oil dependence, improve urban air quality, and support sustainable economic growth [10] [67].

Under these frameworks the government through policy promotes adoption of electric vehicles by restricting importation of ICE vehicles in 2024 as part of Ethiopia's long-term decarbonization agenda. As part of EVs promotion exemption of value-added tax (VAT), excise tax and surtaxes for electric vehicles (EVs) and reduced import duties of key components from 2022. The Ministry of Transport and Logistics (MoTL) initially aimed to deploy 4,800 electric buses and 148,000 electric passenger vehicles by 2030; following rapid uptake enabled by fiscal incentives, these targets were revised upward to nearly 500,000 EVs by 2040 [9].

The Energy Sector Transformation Plan (ESTP) and Ministry of Water and Energy strategies prioritize renewable-dominated electricity generation; hydropower, wind, solar, geothermal, and biomass, which could ensure transport electrification delivers significant emissions mitigation. By integrating EV promotion policies with renewable energy expansion, and import restrictions of ICE vehicles, Ethiopia has established a consistent policy signal that supports climate mitigation targets. This policy context provides the foundation for the present study's quantitative assessment of how EV evolution influences electricity demand, energy system investment needs, and progress toward NDC compliance and carbon-neutral road transport by 2050

CHAPTER THREE

3 METHODOLOGY

The import ban of ICE vehicle would accelerate EV adoption in transport sector, escalating electricity demand that propel additional power generation. The electricity demands as result of EV adoption have its impact on energy system, needs to be planned within unified energy system. This study apply a quantitative energy system modelling under a plausible EV adoption pathways development embedded in economy wide electricity demand. Open-Source energy Modelling System (OSeMOSYS) tool is employed to determine electricity demand for evolution of EVs and to explore optimized power mix configuration for Ethiopian context. The associated annual energy and economy saving as a result of shifting ICE vehicles to EV from 2024 to 2050 is analyzed.

3.1 Material and Methods

3.1.1 Materials

Tools

To determine the additional electricity demand for evolution of EVs and how that could be influence the nation energy system, the study employs Open Source Energy Modeling System (OSeMOSYS). The tools programing follows linear mathematical algorism and takes a bottom-up approach, fed predefined data by the user avoids any endogenous assumption made within OSeMOSYS. OSeMOSYS is full-pledged optimization modeling tool designed to fill a gap in the analytical toolbox of other modelling tools for long-run energy planning, by enabling integrated analysis of energy resources, production, distribution, investments and end-use consumption across sectors [50] [68].

OSeMOSYS was selected because it is a transparent, open-source, bottom-up optimization model capable of endogenously determining least-cost power system expansion while simultaneously representing transport demand growth, policy-driven EV diffusion, technology-specific energy consumption, emissions, and investment requirements. Compared with scenario/simulation-based tools such as the Long-range Energy Alternatives Planning System (LEAP), which does not inherently optimize system-wide investment decisions unless coupled with external optimization tools, and TIMES/MARKA family of model require extensive datasets, advanced technical expertise, and proprietary software environments that may limit accessibility for developing-country applications.

While OSeMOSYS provides sufficient flexibility for users in developing countries or smaller institutions allows user defined customization and configurations, transparency, and computational efficiency required to evaluate long-term transport–energy interactions [69] Thus, to evaluate the three plausible EVs adoption pathways this tool makes it well suited for forecasting EVs charging demand and the associated emission, which is widely applied [31]. As modeling is designed to generate new insights, OSeMOSYS works well as a sandbox for trying out new energy model ideas. It is developed in a series of functional blocks combined to form a customized model component, allows to describe model sets like parameters, variables, constraints, and objectives by using plain English. It could be utilized for policy analysis to explore energy pathways, assess technology options, and evaluate climate strategies [50].

It is good for running alternative scenario analysis stretched over decades, for projections of energy supply and demand by changing assumptions [70]. Its principal application areas include power-sector expansion, transport planning, looking at how sector link together and emissions mitigation analysis [70]. OSeMOSYS complies the recent scientific community requirement of modeling tool transparency and openness for the purpose of reproducibility and publicly acceptable model outputs [50].

The analytical value of this optimization framework can be further enhanced to support direct policy and investment implementation by incorporating additional features, such as operational feasibility constraints, uncertainty and flexibility analysis, improved temporal and spatial resolution, greater technological detail, and macroeconomic impact assessment, and/or by enabling coupling with complementary modelling tools.

3.2 Data Sources and Fleet Characterization

The current vehicle fleet composition were collected from Ministry of Transport and Logistics (MoTL), energy balance and demand projection the Ministry of Water and Energy, petroleum fuel import from Ethiopian Petroleum Enterprise and prices of electricity from Ethiopian electric utilities. The volume of last five year EV imports Ethiopian custom commission. Secondary data such as GHG emission factor for fuel IPCC based, vehicles annual average kilometer, vehicle efficiency from official report of MoTL and vehicle maintenance costs were adopted from literatures.

Fleet characterization disaggregates the road transport sector into major vehicle segments based on operational characteristics, energy consumption patterns, vehicle utilization rates, fuel technology and emission intensities. In this study, fleet heterogeneity is classified into five groups based on differences in energy consumption, emission activity ratios, and load factors as shown Figure 3. These groups include: (i) motorcycles, encompassing two and three wheelers; (ii) buses, including medium and large sized buses; (iii) minibuses; (iv) cars, comprising automobiles, ambulances, and pickup vehicles; and (v) trucks, covering dry and liquid cargo vehicles, trailers, agricultural trucks and machinery, as well as all heavy-duty vehicles excluding the passenger transport vehicles.

This disaggregation enables accurate estimation of energy demand for both ICE and EV fleets and ensures consistency with observed transport activity patterns. Based on the collected data from transport sector the fleets dynamics used in this study is shown in Annex I. The transport demand service usually quantified by indicating the passengers per kilometer for personal mobility and ton per kilometer for goods carrying activities. This implies knowing on one side the distance travelled and on the other the number of travelling people. Forecasting the growth and composition of future vehicle in a country will consider development plan and number of vehicle demanded by passenger on various routes at different times [54] [71].

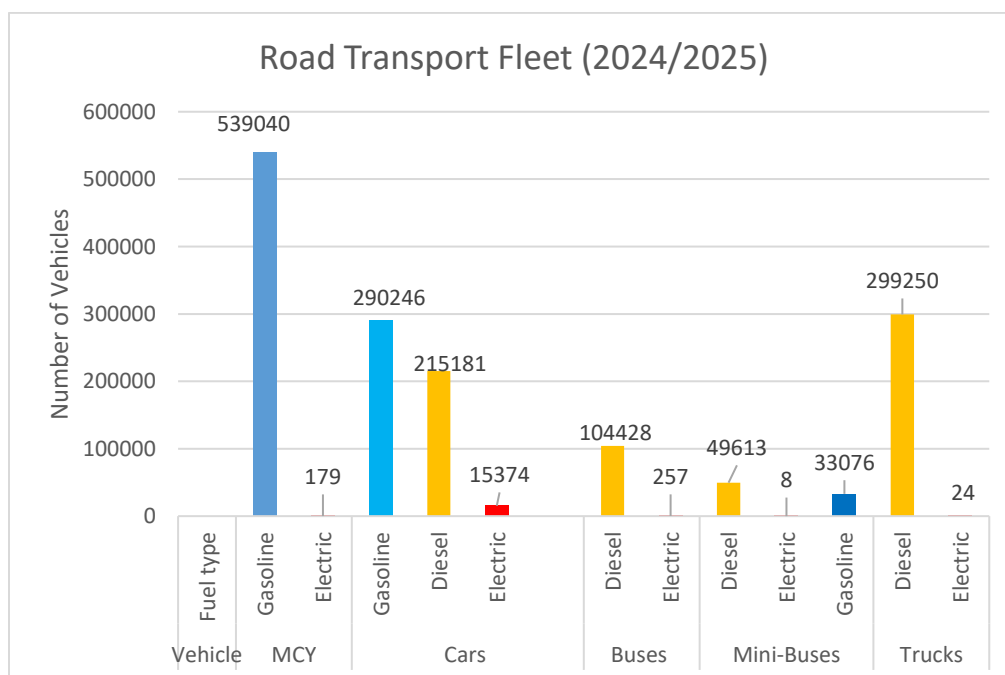


Figure 3: Road transport fleet in 2024/2025

3.2.1 Data quality and Availability

The analysis is based on official data obtained from government institutions requested by letters from the university and internationally recognized organizations, including the IEA, IRENA, World Bank, and peer-reviewed literature. National data set were used wherever available, while internationally accepted techno-economic parameters were adopted only where local data were unavailable. No proxy, synthetic, or arbitrarily generated datasets were used in the study.

All input data, assumptions, and scenario parameters were obtained from documented and traceable sources and were subjected to consistency and cross-validation checks before use in the modelling framework. To ensure transparency and reproducibility, the datasets, assumptions, and sources references supporting this study will be made available through the university institutional repository, including links to publicly accessible original data sources where applicable.

3.3 Analytical Framework and Designing Models

This study employs a long-term, scenario-based energy system modeling framework to assess the impact of electric vehicle (EV) evolution on Ethiopia's national energy system from 2021 to 2050 as depicted in Figure 4 below. The analysis focuses on electricity demand growth, capacity expansion, investment requirements, greenhouse gas (GHG) emission reductions, and energy and economic savings, examining the national energy and climate policy objectives.

The Open Source Energy Modeling System (OSeMOSYS) is used as the primary analytical tool to determine cost-optimal electricity generation and capacity expansion pathways under increasing EV-induced electricity demand. OSeMOSYS represent interactions between transport energy demand, electricity supply, emissions, and system costs. The analysis is conducted under four policy-relevant scenarios: Business-as-Usual, Moderate Transition, Ambitious National Target, and Net-Zero Mobility each reflecting different assumptions regarding policy strength, electricity supply mix, and emission mitigation goals.

The modelling tool is calibrated using historical data for the period 2021–2024 to ensure consistency with observed vehicle stocks, energy use, and generation capacity. Following calibration, simulation carried out for optimal expansion configuration of Ethiopia's energy system onward to 2050. This integrated framework enables a consistent assessment of how EV adoption

reshapes transport energy demand, drives renewable-dominated electricity expansion, reduces emissions, and delivers long-term economic benefits at the national level.

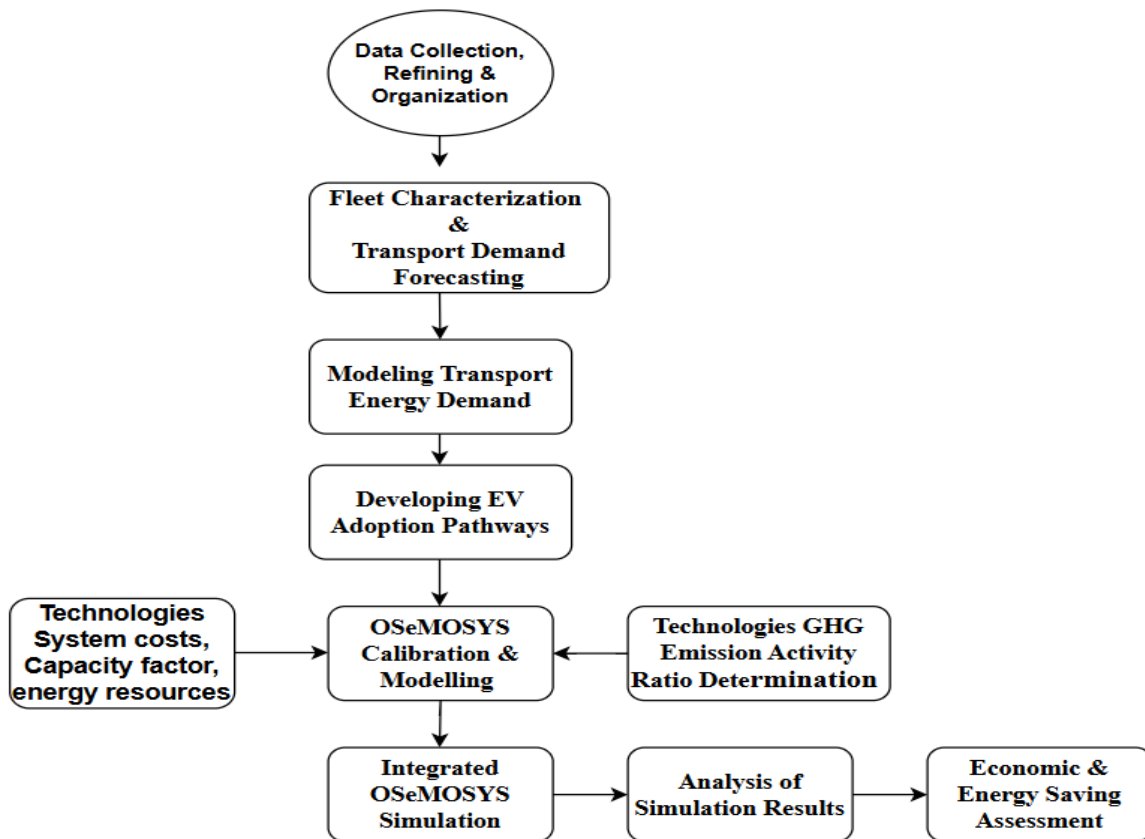


Figure 4: schematic process of the methodology followed in this study

3.3.1 Vehicle Ownership and Fleet Evolution Modeling

A range of factors influence the future growth and composition of the vehicle fleet under the current policy framework. Key determinants include the rate of economic growth (GDP), per capita income and household income growth, which particularly affect demand for vehicles and private vehicle affordability; and the availability of foreign currency, which currently constrains vehicle imports [38]. Historically the vehicle ownership (number of vehicles per 1000 people) was 6 & 130 in Ethiopia and Addis Ababa respectively, with motorization rate of 240 in Addis Ababa in 2016 [21].

Vehicle ownership is modeled using Gompertz function to projected future transport demand, which relates vehicle ownership to GDP per capita to economic growth. This approach captures slow and rapid growth income constrained effects, and eventual saturations at higher economic

levels due to urban congestion, policy limits or modal shift. In this context, it is applied to estimate vehicle ownership using the equation in (1) [19], [21] [17].

$$\epsilon_t = S e^{-\alpha e^{-\beta I(t)}} \quad (1)$$

Where, ϵ_t represents the vehicle ownership (vehicles per 1000 people) in time t (year); S is the maximum saturation level of vehicle ownership (vehicles per 1000 people). The Gompertz parameters α & β were estimated by linearizing the ownership function and applying ordinary least squares regression to historical vehicle ownership and GDP per capita ($I(t)$) data. The scaling factor (α), elasticity of ownership (β) and ϵ_t changes in proportion to the change of S . The historical GDP per capita ($I(t)$) is sourced from the World Bank and its projection to 2050 is assumed that it will continue the current growth trend [72]. Vehicle stock growth is modeled using a compound growth formulation, using annual vehicle ownership growth rate.

$$V(t) = V_0[1 + r(t)] \quad (2)$$

Where: $V(t)$ is vehicle stock at time (t), V_0 is initial vehicle stock and $r(t)$ represents the vehicle ownership growth rate Annex I. Road transport fleet dynamics.

3.3.2 EV Transition Modeling

Future EV transition is modeled as a policy-driven technology diffusion process embedded within growth of the national vehicle fleet, rather than as an independent EV growth trend to prevent common modeling error of decoupling EV increment from transport demand growth. Total vehicle demand growth is taken exogenously from projected fleet expansion discussed in section 3.3.1, while EV penetration is endogenously determined using a logistic diffusion function calibrated to Ethiopia's transport electrification targets. Historical fleet composition data are used only to establish baseline EV shares, avoiding extrapolation of early adoption trends. Annual EV stock is derived as the product of total vehicle fleet size and evolving EV share, determined as

$$N_{EV}(t) = S_{EV}(t).V(t) \quad (3)$$

Where: $N_{EV}(t)$ is the number of EV at time (t), $S_{EV}(t)$ is share of EV at time (t) and $V(t)$ the total vehicle at time (t). EV numbers grow only because the fleet grows and policy shifts technology choice to EV. While EV transition is using a logistic diffusion function (S-curve) reflecting early adoption barriers, rapid mid-transition growth and market saturation under policy enforcement given by [73], [74] ;

$$S_{EV}(t) = \frac{S_m}{1 + e^{-k(t-t_0)}} \quad (4)$$

Where: S_m is the maximum EV share (saturation) and S_0 is the initial EV share and k is transition speed. For adoption pathways discussed in section 3.3.4 S_m is 85% (policy target by 2040) [37] and S_0 the current (2024) EV share 1.02% considered Annex I. Road transport fleet dynamics. Anchoring policy embedding parameters: the ICE vehicle import ban, EV fiscal incentives, NDC commitment, and carbon-neutral transport ambition. The adoption rate (k) is calibrated from current EV share and policy target as discussed in section 3.3.4 (adoption pathways) below from equation 4.

3.3.3 Transport Energy Demand Modelling

Transport energy demand is calculated as final energy consumption by vehicle segment, measured in passenger-kilometers and ton-kilometers for total vehicle stocks determined in section 3.3.1. Energy consumption for both ICE and electric vehicles is determined on a segment-specific basis accounting for vehicles efficiency and expressed as energy intensity (MJ/km) [75][[76].

For OSeMOSYS-based modelling, vehicle energy demand is expressed as energy consumption per unit of transport activity; specifically, demand is calculated in petajoules (PJ) per billion passenger-kilometers for each vehicle class, covering both internal combustion engine (ICE) and electric vehicles (EVs). This is derived as the product of total fuel and/or electricity consumption measured in (PJ), consistent with the model's energy unit and the corresponding technology efficiency, expressed in billion passenger-kilometers per petajoule (Gpkm/PJ) [77] see Annex I.

$$TD = \sum(E_C \cdot \eta_T) \quad (5)$$

Where: TD is aggregated annual transport energy demand from all road vehicle segment in petajoule(PJ), E_C is energy (fuel and electricity) consumption (PJ) for a given vehicle segment [75] and η_T is the efficiency of technology (vehicle type/classes). The technology efficiency (η_T) used billions of vehicle kilometer traveled in a year per petajoule (Gvkm/PJ is multiplied with load factor (average number of passenger or tone per vehicle) (p/v) [77]. The activity and load factor, and energy intensity adopted within the model are sourced from national data [3] see Annex I.

$$\eta_T \left(\frac{Gpkm}{PJ} \right) = \left(\frac{Gvkm}{PJ} \right) \cdot \left(\frac{p}{v} \right) \quad (6)$$

The transport demand growth for each vehicle segment from 2025 to 2050, as determined by equation (2) in section 3.3.1, is translated into corresponding energy demand using Equation (5).

For the gradual EV transition scenarios, the shift from internal combustion engine (ICE) vehicles to electric vehicles (EVs) is represented by reallocating the associated energy consumption from ICE technologies to EV technologies.

3.3.4 EV Adoption Scenarios

The EVs adoption pathways were not intended as forecasts of single future outcome or prediction of EV ownership; rather, they were constructed as policy-consistent transition pathways to evaluate the sensitivity of Ethiopia's energy system to different electrification ambitions. The assumption are grounded in three considerations: (i) the current EV penetration level of 1.02% in 2024, (ii) the government targets to adopt 0.5 million electric vehicles by 2035 (iii) the government's transport electrification target of achieving 85% by 2040, and (iv) Inter-governments climate mitigation strategies under the Paris agreement to collectively achieve the 1.5°C goal. The purpose of this pathways is not predict the exact future EV share, but to evaluate how different policy ambitions and technology diffusion rates influences Ethiopia's long-term energy system development, investment needs, and climate outcomes within a consistent fleet-growth framework. Accordingly EV penetration was represented using logistic diffusion function embedded within projected vehicle fleet growth.

Thus study investigates three EVs adoption scenarios in addition to businesses as usual (BAU): Moderate Transition, Ambitious National Target and Net-Zero Mobility by embedded within a baseline entire economy demand. The transport electrification include the five vehicle segments from the current share in each segments. Transitions from internal combustion engine (ICE) vehicles to electric vehicles (EVs) under each pathway are, the corresponding electricity demand is explicitly derived and simulated using the OSeMOSYS framework embedded within entire economy wide rather than separately to assess the incremental impacts of transport electrification on Ethiopia's energy system. The resulting scenarios provide a structured basis for evaluating long-term energy demand implications and system-level responses under alternative transport decarbonization pathways defined below.

I. Baseline (Business-As-Usual – BAU):

EV adoption grows only per existing market momentum: only 15842 EVs in 2024 ($\approx 1.02\%$ of the total fleet) operating on the road among over 1000,000 EVs imported for the last five years. The baseline scenario characterizes number of EV increases onward to 2050 as the total vehicle

demand grows with the current EVs share ($S_{EV}(t) = 1.02\%$) as discussed in section 3.3.2 above. This case characterizes modest transition of EV, given the technological and charging infrastructure challenges to be faced for EV adoption, and fuel imports remain high (~\$4–6 billion annually). This pathway reflects existing government commitments and the current policy framework, including the ICE vehicle import ban introduced in 2024 and fiscal incentives such as customs duty exemptions (15% for fully assembled EVs, 5% for semi-knockdown (SKD), and 0% for locally assembled completely knocked-down (CKD) vehicles) [55] [78]

II. **Moderate/Optimized Transition**

In this scenario, electric vehicle (EV) penetration increases gradually but at a more optimistic pace than in the baseline, reaching approximately 3% of the total vehicle fleet by 2030, 14% by 2040, 25% by 2045, and around 40% by 2050. This pathway considers the government targets to transition 500,000 internal combustion engine (ICE) vehicles including private, light commercial, and public transport fleets to EVs by 2040 [37], [79]. This pathway assumes improved yet realistic coordination among government institutions, the private sector, and energy and utility providers, resulting in a moderately accelerated EV adoption.

The scenario further assumes moderate technological and infrastructure development, supported by renewable power expansion from major projects such as Grand Ethiopian Renaissance Dam and Koysha Hydropower Project, alongside scaled deployment of solar and wind generation. Charging infrastructure expansion is expected to align with national targets, aiming for the installation of charging stations at intervals of 50–120 km by 2040 [37], [79].

III. **Ambitious National Target**

This scenario basically assumes national target follows through on its plan to replace 85% of gasoline and diesel vehicles with EVs by 2040. The transition starts slowly from just over 1.02% in 2024 to about 10% by 2030, then accelerate reaching ~44% by 2035 and finally achieves 85% of vehicles in 2040. This pathways characterized by strong government push, foreign investment, and international climate funds, and large private sector engagement. Public transport, taxis, and delivery fleets get priority through subsidies, fleet conversion programs, and creative financing to bring down the purchase expenditure of EVs.

This scenario also assumes the manufacturing and charging infrastructure gradually builds up domestic EV and battery assembly, moving from semi-knocked-down to fully knocked-down

operations around 2035, facilitating secure supply and bring down costs. Charging stations are planned every 50–80 kilometers along major highways, with coverage reaching most cities by 2035–2040. New buildings have to meet EV-ready standards, and urban hubs like bus terminals and parking lots get chargers, alongside solar-powered highway stations and smart-grid pilot zones. At the same time, transport electrification is closely aligned with grid modernization by 2040, and the electricity supply is from renewables; with daytime solar surplus deliberately used to meet peak EV charging demand, backed by time-of-use rates and supportive regulations. And as battery pack prices expected to fall below \$100/kWh [80], thus EVs become more affordable.

IV. Net-Zero Mobility (System Shift)

This scenario represents a deep system-wide transformation of the transport sector in Ethiopia, which goes beyond vehicle electrification to a fundamental redesign of mobility systems. Electric vehicle (EV) penetration accelerates sharply from the current share to approximately 13% of the total fleet by 2030, 57% by 2035, reaching 88% by 2040, and exceeding 99% by 2050. By mid-century, virtually all road transport activity is electrified, supported by a comprehensive transition away from internal combustion engine technologies. EVs will dominate new-vehicle sales in urban areas by 2030, and by 2040, the transport system will be largely green and integrated into a broader clean-mobility framework.

This pathway considers structural shifts in mobility demand that facilitates technology transition. The scenario characterizes private vehicle driving declines in major urban areas and shared mobility by buses and taxi powered by electricity are replaced for mobility demand. The hydrogen fuel-cell, CNG propulsion and other technologies are deployed for long-haul and heavy trucks. To facilitate EV adoption public transports, taxi services and freight operations are supported with the provision of loan and also public-private investment share grows rapidly for domestic EV assembly, manufacturing of spare parts and battery, related electrification logistics. The Power supply sector aligned with renewables, and grid modernization handles charging congestion and time of use tariffs.

3.3.5 GHG Emission Reduction Analysis

Determination of the quantity of GHG emission reduction by shifting ICE to EV is performed by simulating OSeMOSYS tool for each scenario discussed in section 3.3.4. The type of GHG (CO₂, N₂O & CH₄) and the emission factor (upper values of the IPCC guideline for gasoline and diesel

fuels) were considered since the fuel used in Ethiopia has high Sulphur content and older aged vehicles adopted from Ministry of Transport and Logistics (MoTL) [3].

Then the emission activity ratio (see Annex I.) which is the product of input activity ratio of transport technology and GHG emission factor of the fuel type is fed to the OSeMOSYS tool for simulation. Emission reductions are quantified by comparing scenario results against the BAU pathway. This approach enables assessment of progress toward Ethiopia's Nationally Determined Contribution (NDC) and long-term carbon-neutrality goals [6].

3.3.6 Economic and Energy Saving Assessment

The Energy savings are calculated as the difference in total final energy consumption between adoption scenarios and the BAU case. Economic savings are estimated from an operational perspective, focusing on avoided fuel imports, electricity costs, and maintenance expenditures. Determination of total energy saved from shifting ICE to EV under each scenario performed by summing energy saved in each vehicle segments 3.3.1. Thus the energy saving from a given vehicle transition of ICE to EVs is the differences of total energy (fuel displaced per litter in (kWh) and electricity drawn from grid in (kWh) accounting with losses of charging) consumed in baseline and adoption scenario given as:

$$\Delta E = E_{BAU} - E_{Scen} \quad (7)$$

Where: ΔE is energy saved, E_{BAU} is the total energy consumed in baseline scenario and E_{Scen} is the energy consumed in adoption scenarios. The energy consumed by each vehicle segment is determined as:

$$E_i = E_i^f + E_i^g = N_{ICE\ i} \cdot \lambda_{ICE\ i} \cdot D_i \cdot LHV_f + \eta_{chg} \cdot \lambda_{EV\ i} \cdot N_{EV\ i} \cdot D_i \quad (8)$$

Where E_i is the total energy consumed in TWh for the i^{th} vehicle segments (see section 3.3.1), E_i^f is fuel energy consumed and E_i^g is the electricity drawn from the grid, F_i is fuel oil consumed by the i^{th} ICE vehicle in (L) and LHV_f is the lower calorific (heating) value of fuel oil (kWh/L), η_{chg} the charging multiplier from grid drawn per kWh delivered to wheels; i.e., fractional losses and $\lambda_{EV\ i}$ energy efficiency (electricity consumption by EV per kilometer (kWh/km)) [81], [82],[83], $\lambda_{ICE\ i}$ efficiency (the fuel consumed by the i^{th} ICE vehicle per kilometer (l/km) [21] [82],

[83], [84], $N_{EV\ i}$ & $N_{ICE\ i}$ is the number of EVs and ICEs in i^{th} vehicle segments and D_i is the annual average distance traveled by the vehicle segment.(Annex I.).

The economic savings associated with the transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) are evaluated from an annual operational cost perspective, excluding vehicle purchase prices, insurance and loan interest costs, and vehicle tax, which are usually used for total cost ownership. This study focuses on operational costs, namely fuel and electricity costs, routine maintenance and repair expenses, annualized battery replacement costs, and charging-related energy losses. Accordingly, economic savings are defined as the difference in total annual operating costs between the baseline (ICE-dominated) scenario and alternative electrification scenarios, given by:

$$\Delta C = C_{BAU} - C_{Scen} \quad (9)$$

$$C_i = \left((F_i \cdot P_f) N_{ICE,i} + (N_{ice,i} \cdot C_{mr_{ICE}}) \right) + \left((E^g_i \cdot P_e) N_{EV,i} + A_{bat} + (N_{EV,i} \cdot C_{mr_{EV}}) \right) \quad (10)$$

Where: ΔC is the cost saved, C_{BAU} & C_{Scen} are the total operational costs in bassline and adoption scenarios, and C_i is the total cost spend for the i^{th} vehicle segment, F_i is the fuel consumption for ICE, E^g_i is total electricity drawn from the grid for EV, P_f is fuel price per liter (\$/L) [85] and P_e is electricity price per kWh (\$/kWh (Annex I.), and $N_{ICE,i}$ & $N_{EV,i}$ are the number of vehicle for ICE and EV, and $C_{mr_{ICE}}$ & $C_{mr_{EV}}$ are the respective routine maintenance and repair cost per vehicle for ICE and EV [86] . While A_{bat} is annualized battery cost for EV, to account for battery replacement within annual operating costs the battery replacement capital costs converted using the capital recovery factor (CRF)), given by [87]:

$$CRF(r, N) = \frac{r(1+r)^N}{(1+r)^N - 1} \quad (11)$$

$$A_{bat} = C_{bat} \cdot CRF(r, N) \quad (12)$$

Where: r is discount rate, N represents the battery amortization period, typical battery lifetimes, and C_{bat} denotes the capital cost of battery replacement, , defined as the full replacement cost of the battery pack for a given vehicle. The change in future fuel and electricity price are determined using equation (13) from historical compound annual growth rate. The fuel price growth rate is used determined from historical global price and national historical data is used for electricity price growth rate.

$$P_t = P_0(1 + r)^{(t-t_0)} \quad (13)$$

3.3.7 Model Calibration and Simulation

To address the research question and achieve the study's objectives, a linear mathematical modeling tool, OSeMOSYS, is employed. This optimization modeling tool is used to analyze three plausible scenarios by exogenously inputting data related to energy demand, technology performance, costs and environmental impacts.

The model is calibrated using historical data for 2021–2024 to ensure consistency with observed energy system performance. Simulation period spans from 2021 to 2050, providing a long-term view of Ethiopia's energy system transition under different climate ambition levels. Following the calibration period, then the model is free to optimize system expansion and operation independently under each scenario. Then optimized simulation output generated using the OSeMOSYS tool under the scenarios described in section 3.3.4 are summarized in results section.

The yearly energy demand for each vehicle segments determined based on activity and load factor, and energy intensity used as discussed in 3.3.3 see **Annex I**. The activity factor for vehicle classes considered the average yearly distance travelled by each vehicle segments in Ethiopia. The energy demand for road transport do increases as the total transport demand increase through years in modelling period. And also the energy demand for the gradual transition of internal combustion engine (ICE) vehicles to Electric Vehicles (EVs) was determined by transposing the corresponding energy consumption of ICE vehicles, considering the significant efficiency advantage of EVs over ICE vehicles.

3.3.8 Model Validation and Verification

Given the long-term and scenario based nature of this study, direct validation of future outcome is inherently not possible. Therefore, the credibility of the modelling framework was established through a multi- level approach comprising historical calibration, policy consistency assessment, benchmarking against national planning studies, comparison with published literature, and scenario-based robustness analysis.

First, the analytical framework was calibrated using historical data for the period 2021-2024 to ensure consistency with observed vehicle fleet composition, transport activity, electricity demand, and generation capacity. The vehicle ownership model was calibrated using historical GDP per

capita and vehicle ownership data, while the EV diffusion model was anchored to the observed EV share in 2020 and national transport electrification targets. Similarly, OSeMOSYS model was calibrated to reproduce the existing structure of Ethiopia's power system and electricity demand conditions before undertaking future scenario simulations.

Second, the modeling assumptions and the projected trends were assessed for consistency with national policy and planning document, including Ethiopia's electric mobility strategy, climate resilience green economy (CRGE) strategy, nationally determined contribution (NDC), and national power sector development plans. This ensured that the scenario pathways remained aligned with officially recognized transport, energy, and climate objectives.

Third, Key outputs of the model, including electricity demand growth, renewable energy deployment, generation capacity expansion, investment requirements, and emission trajectories, were benchmarked against available national and energy planning studies. Particularly attention was given to evaluating whether the projected long-term trend remained within plausible planning ranges reported by government institutions and previous modelling literatures. The differences in quantitative outcomes were assessed in relation to variation in modelling scope, technology assumption, and the explicit representation of EV-induced electricity demand in the present study.

Fourth, the modelling results pattern were compared with finding reported in international literature on transport electrification, energy system optimization, and integrated transport-energy modelling. The use of the Gompertz vehicle ownership model, logistic technology diffusion model, and OSeMOSYS optimization framework follows approaches widely applied and validated in previous studies for long-term transport and energy system analysis. Consistently in this direction coinciding the result pattern and magnitude of major trend with published literature provided additional confidence in the reliability of results.

The scenarios were developed based on policy-consistent pathways to evaluate the sensitivity of electricity demand growth, power system expansion, emission mitigation, energy saving and investment requirement under alternative transport electrification rather to predict a single future outcome or EVs ownership. The stability of major trend and conclusion across these pathways demonstrate the robustness of the modelling framework and strengthens confidence in the resulting policy insights. Furthermore, the convergence of evidence from historical calibration, consistency with national policy objectives, benchmarking against national planning studies, comparison with

international literature, and scenario-based sensitivity analysis indicate that the framework provide a credible and reliable representation of the long-term interaction between transport electrification and Ethiopian's energy system.

3.3.9 Key Assumptions Rationale

The cost assumptions made in this thesis for running the OSeMOSYS tool for power technologies are grounded in internationally recognized datasets from both the IEA and IRENA. Capital expenditure (CAPEX) and fixed operation and maintenance (O&M) costs for all major power generation technologies were primarily obtained from IEA technology cost datasets, while technology-specific escalation and cost decline trends from 2020–2024 were derived from IRENA renewable energy cost reports as shown Annex II. Based on the current global unpredictability in political and economic conditions, the trends in technology-specific escalation and cost declines are applied for the year from 2021 to 2025 and held constant for the rest of modeling period to allow the tool freely optimize the selection and configuration of technologies. This combined approach ensures consistency between current global benchmark costs and observed technological learning trends.

The capacity factors of renewable power technologies vary by time of day and season (see Annex II); they are derived from existing installed capacities and subsequently adjusted using literature data. And for developing economy the vehicle ownership is assumed conservatively to be 40 by 2050 and the population growth rates 0.045 (see Annex III).

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1 Result

4.1.1 Transport Demand growth

The transport demand (vehicle) growth determined from vehicle ownership (number of vehicles per 1,000 people), based on the current vehicle stock (1.55 million), see section 3.2, the transport demand will grow to 4.92 million by 2050 with the vehicle growth rate of 0.05 in 2025, which gradually decreases to 0.03 by 2050 as vehicle ownership saturates, as shown in Figure 5. The corresponding total population growth will reach 250 million by 2050, based on World Bank growth rate.

The estimated Gompertz diffusion pattern remain below the inflection point of motorization curve, that is why it exhibits convex, pre-transition pattern rather than a full S-shaped, reflecting that Ethiopia is in an early stage of motorization. From historical vehicle ownership of 6 vehicle per 100 people in 2016, it grew to 10 in 2024, and projected to reach about 40 by 2050.

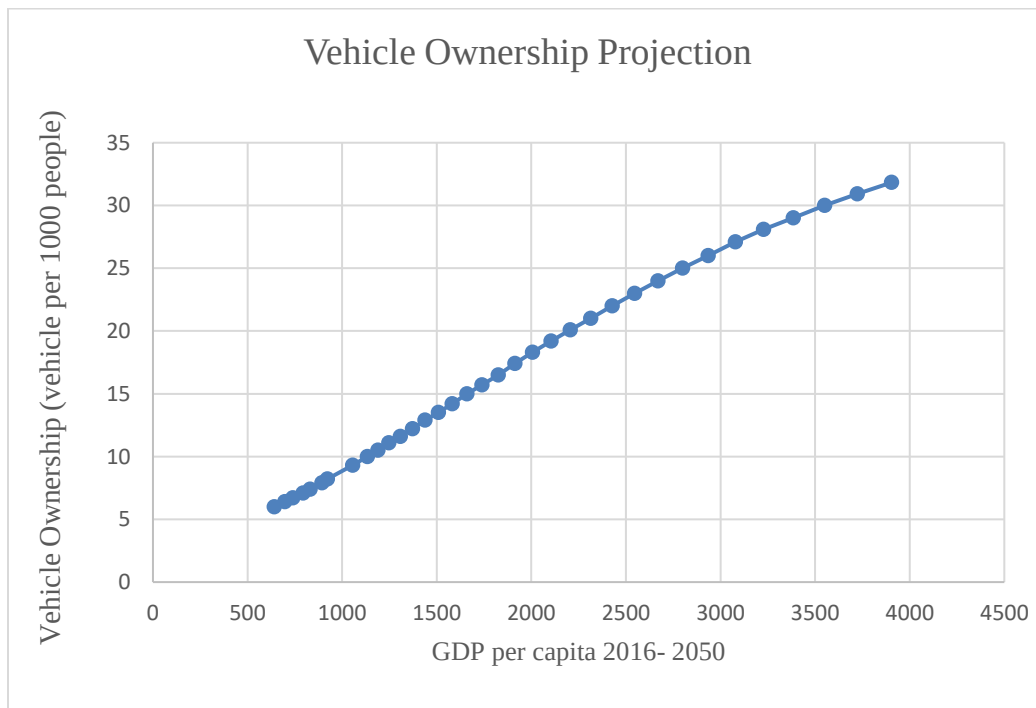


Figure 5: Vehicle ownership growth

From the logistic diffusion function the number of electric vehicle (EVs) grows from 15,842 in 2024 to 50,215 by 2050 under baseline case, its share remains 1.02% of the total fleet size, and the EVs number increase as the total fleet size grows. In contrast the moderate adoption pathway shows gradual transition to EVs, the share increase to 11.84% by 2040 and 40% by 2050, the corresponding EVs number reaches nearly 2 million within the expanding total fleet as shown in Figure 6 and Figure 7.

The ambitious and net-zero pathways demonstrate a clear S-curve pattern of EV transition, characterized by slow early growth, rapid acceleration, and eventual market saturation. EV share grows slowly before 2030 reaches 9.9% and 12.7% in ambitious and net-zero pathways and increase rapidly during 2030- 2040 by about 85% for ambitious pathways. The full electrification shows total market penetration, transition pathway replace nearly all ICE vehicle to EV with share of 99.9% by 20250. The transition to EVs occurs alongside within continued growing transport demand as seen in Figure 6 and Figure 7. These EVs adoption pathways were not intended as forecasts of single future outcome or prediction of EV ownership; rather, they were constructed as policy-consistent transition pathways to evaluate the sensitivity of Ethiopia’s energy system to different electrification ambitions set by the transport sector.

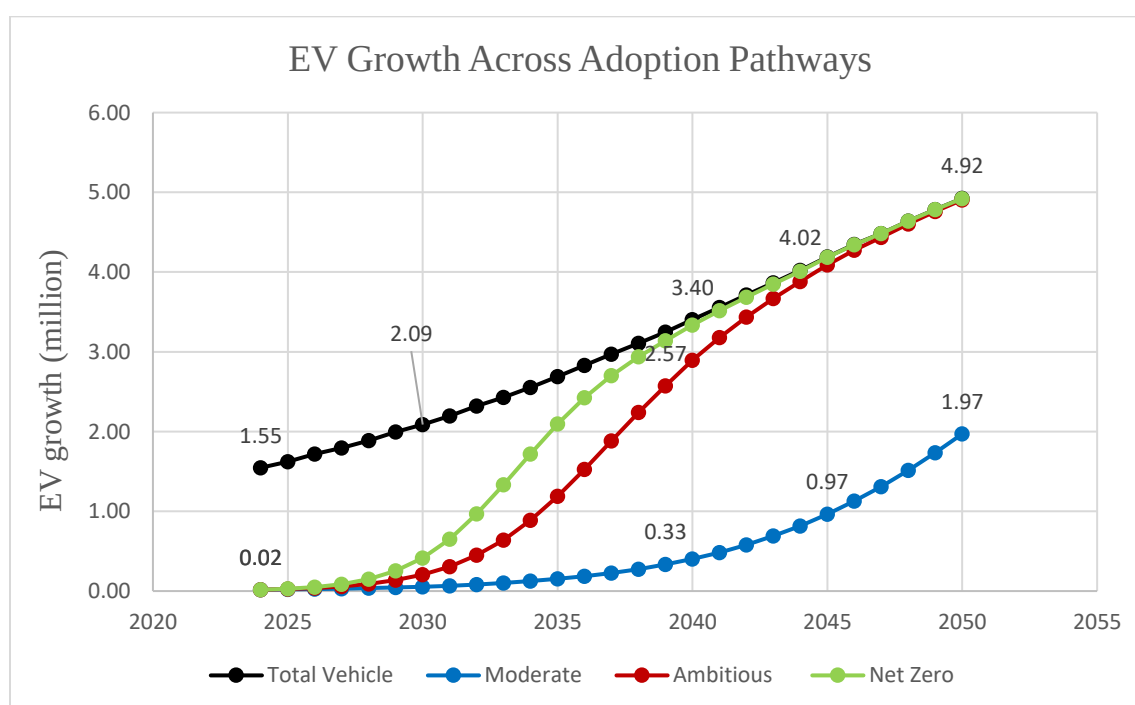


Figure 6: Vehicle demand growth and transition to EV

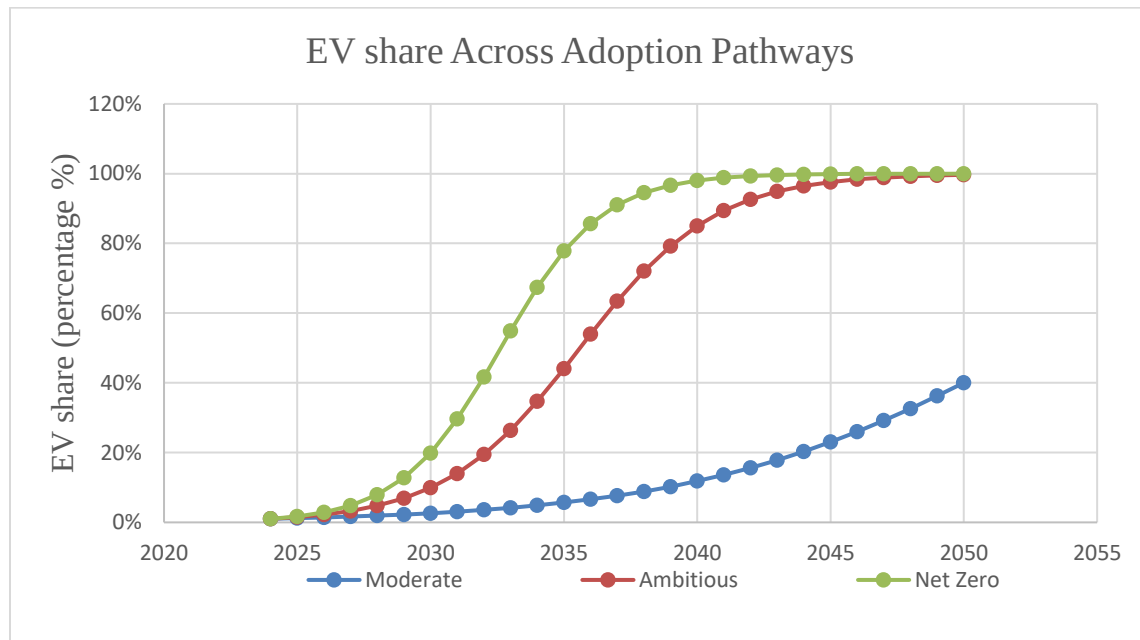


Figure 7: EV share growth

4.1.2 Energy Demand and Investment Required

The optimized output of OSeMOSYS simulation model for the adoption pathways described in section 3.3.4 are evaluated comparatively against the baseline demand. The modelling framework designed address the objective of this study, to evaluate strategic implication of transport electrification on Ethiopia’s long-term energy system and therefore does not explicitly represent short-term EV charging demands, such as hourly, daily or peak-load profiles, which usually used to analyze grid performance.

The long-term energy system dynamics and associated greenhouse gas (GHG) emission trajectories were assessed using four key performance indicators: total installed capacity, electricity generation by technology, annual investment costs, and annual emissions across all technologies. These indicators capture the system’s physical expansion, technology mix, financial requirements, and environmental outcomes associated with meeting e-mobility demand and achieving emission reductions relative to the business-as-usual (BAU) pathway. The results are presented through summary charts in the following subsection, illustrating the relative performance and system-level implications of each scenario under the defined assumptions.

Capacity Expansion

When analyzing road transport electricity demand in isolation (i.e., separately from the rest of the economy), the existing generation capacity (7GW) is sufficient to meet electricity demand under transport business-as-usual (BAU) scenario. In contrast, when simulating transport electrification as part of the broader economy, capacity must expand nearly from 150 GW to 175 GW by 2050 across EV adoption pathways to satisfy the economy-wide power demand, as shown Figure 8.

Under the moderate (40% EV adoption) scenario, the electricity demand increases moderately with capacity addition of 12.64 GW, reaches 162 GW by 2050 and 58 GW by 2040. In this pathway the power supply mix is from renewable with contribution of solar 43%, hydropower 26%, wind 24.7%, and geothermal 6.17% with modest addition from biomass in the year 2050. The ambitious (85% EV adoption by 2040) pathway, the capacity expansion reaches 118 GW with capacity addition of 60.7 GW & 70 GW relative to moderate adoption pathway and baseline case in the same year, respectively. In this pathways solar sources become the leading source of power supply mix with 53.5%, wind 33.78%, geothermal 8.5% and hydro 4.3% with modest contribution of bioenergy in the year 2040; however, onward to 2050 hydropower generation expansion grows to 28% to meet the e-mobility power demand.

The transport net-zero scenario exhibits the largest expansion, the full transport electrification embedded within economy-wide baseline requires nearly 175 GW by 2050 with capacity addition of 12.5 GW & 25.2 GW relative to moderate adoption and baseline case in the same year. Such rapid capacity additions begin in the third decade, dominated by solar with 41%, hydro 27%, wind 23.5% and geothermal 5.87% averaged across adoption pathways, and also contribution of nuclear 2.5% in higher adoption pathways (ambitious and net zero) with modest contribution of bioenergy to enhance system flexibility. In general, high EV adoption pathways demands largest capacity addition of 43 GW from the base line cases by 2050 to meet transport electrification with economy-wide energy demand driven by population and economic growth, as shown in Figure 8.

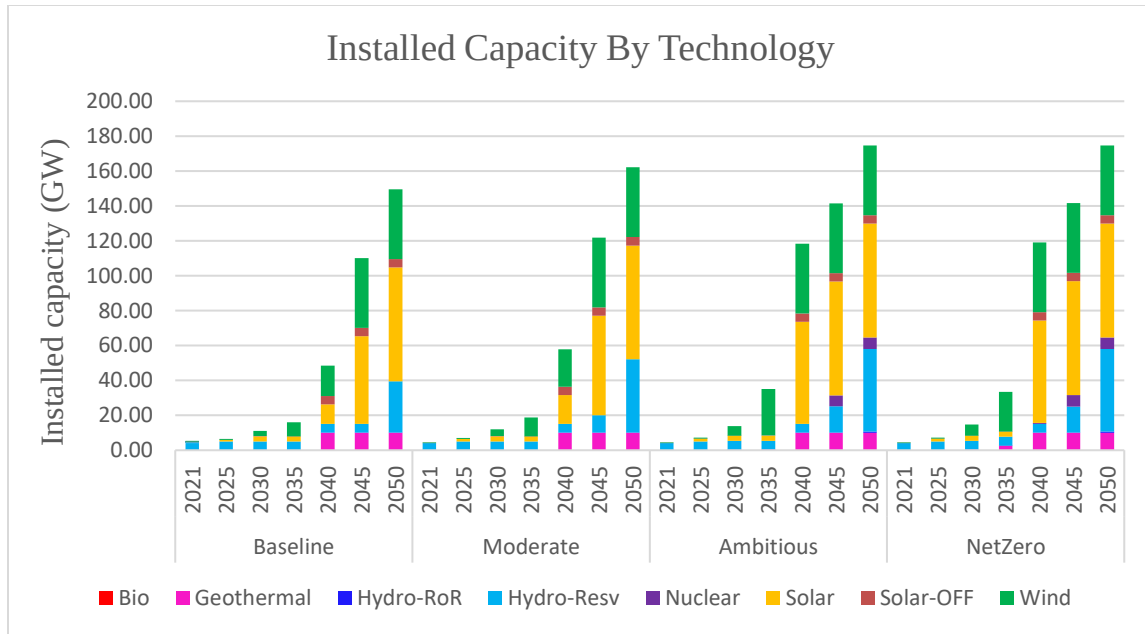


Figure 8: Capacity expansion for EV Adoption pathways

Energy Production

Energy generation patterns across the modeled pathways closely mirror the power expansions in installed capacity to respond the growing demand for electric mobility, as shown in Figure 9. The energy generation will grow from 301TWh in baseline case to 351TWh in moderate and 426TWh in net zero pathways by 2050 as shown in Figure 9. Whereas in ambitious scenario it will demanded 199TWh by 2040, comparatively 125TWh, 136TWh and 203TWh of energy production is demanded in the same year for baseline, moderate and net zero scenarios respectively.

Even if the major capacity expansion was solar as shown in Figure 8, hydropower from both run-of-river and reservoir-based remains the dominant energy source of in all case nearly 43.6% coverage across adoption pathways followed by solar and wind with same contribution of 16% and geothermal with 16.6% across scenarios, while nuclear contribute 6% in high adoption pathways contributes, with modest addition of bioenergy in all cases.

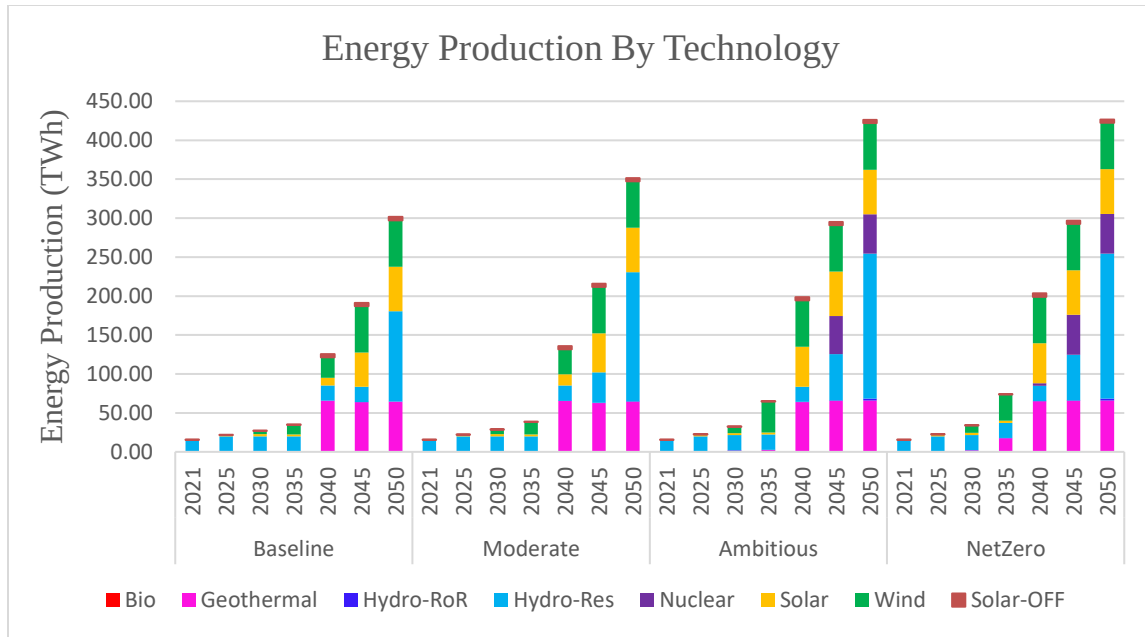


Figure 9: Energy production by technology for EV Adoption pathways

The electricity demand associated with EV adoption pathways were represented as a deterministic input to OSeMOSYS and therefore does not explicitly account for uncertainty in vehicle utilization, charging behavior, charging efficiency or loss. However, the projected electricity demand and resulting capacity expansion requirements are sensitive to several key assumption, particularly, the change in annual vehicle kilometer travelled, improvement in vehicle efficiency and charging system losses. Assuming all other parameters unchanged and, the combined effect of these uncertainties could produce arrange of electricity demand and capacity expansion outcomes around a central estimates presented in this stud. Nevertheless, the overall direction of this result is expected to remain unchanged, with higher EV adoption pathway consistently requiring greater electricity generation and capacity expansion than lower adoption Pathways. Thus future studies recommended to address consideration of these uncertainties.

Investment Required for Capacity Expansion

The investment requirements for capacity expansion and generation mix expressed above in (Figure 8 & Figure 9) will grow progressively with the rate of EV adoption across scenarios. The cost for power generation to meet rising electricity demand for entire economy driven by population growth and urbanization in the baseline case including the existing EV charging demand will require a cumulative of \$42 billion by 2050 as seen in Figure 10. The investment cost

for electricity generation increase with rate of EV adoption to meet the charging demand, it will cost \$52.6 and \$64.2 billion in moderate and net zero scenarios by 2050, similarly in ambitious scenario demands the most rapid capacity expansion, requiring the generation investment costs of \$21 billion by 2040 relative to \$11.6 and \$13 billion in baseline and moderate scenarios in the same year.

Each scenario’s unique capacity expansion pathway determines the composition of power technologies and cost of the required generation asset investments as seen in Figure 11. The majority (55%) of the rising investment driven by hydropower across adoption pathways followed by solar with 14.7%, wind with13.3% and 11.5% for geothermal technologies expansions across EV adoption pathways, and 5.26% for nuclear technologies in higher adoption cases. The costs associated with transmission and distribution expansion and current urban corridor illumination electricity demand are not captured due to data limitations and would represent additional financial requirements.

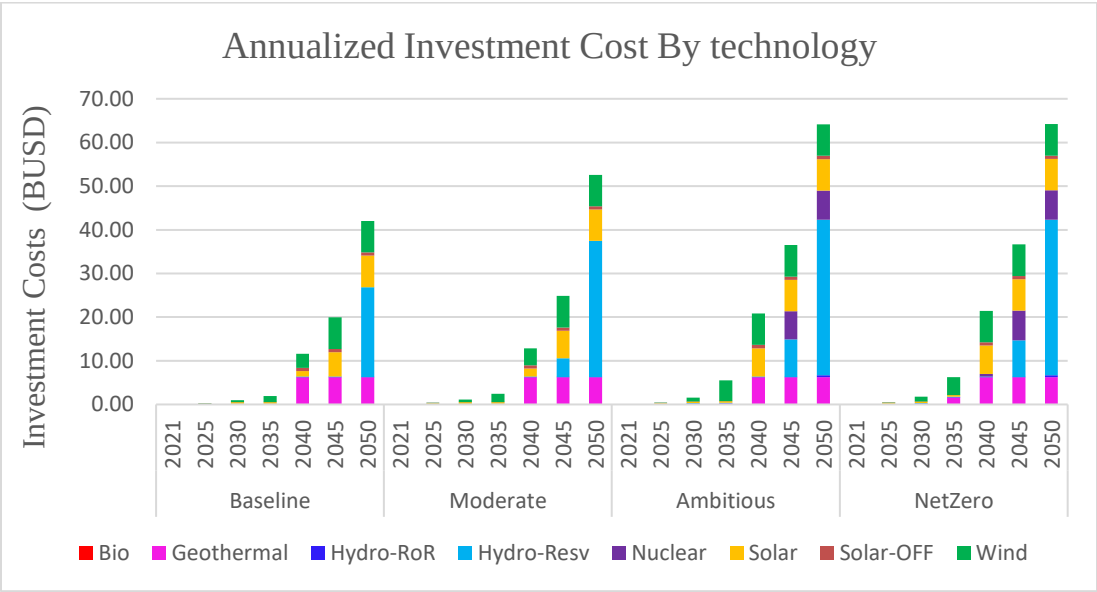


Figure 10: Investment required by technology type

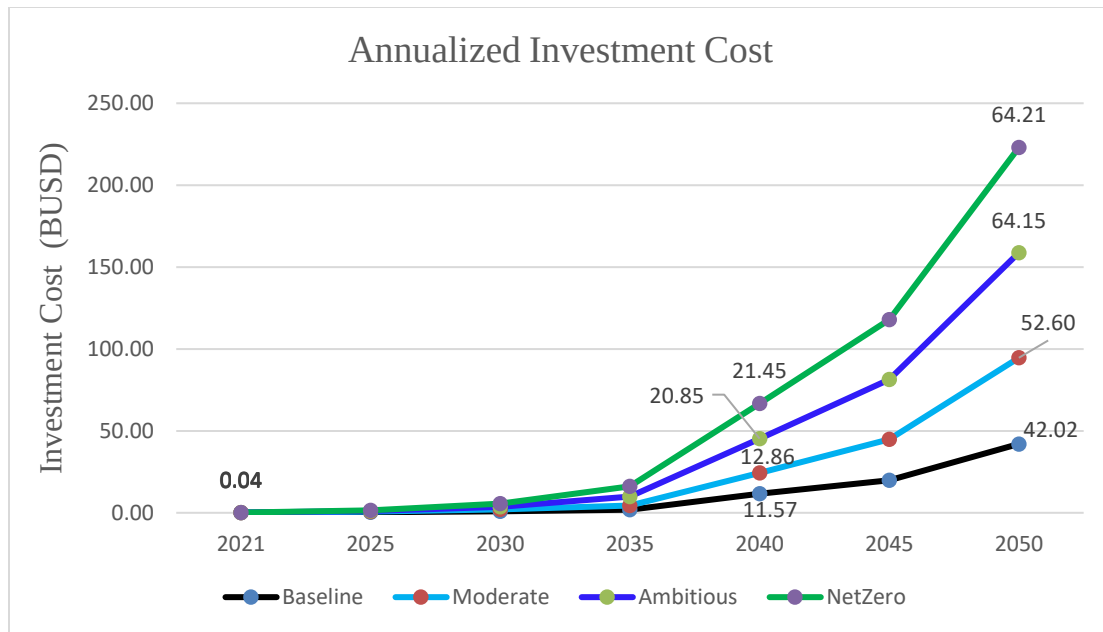


Figure 11: Annualized investment costs for electricity generation mix

4.1.3 Emission Mitigation

The emission mitigation from transport electrification are dominated by decline in carbon dioxide (CO₂) which includes carbon monoxide (CO), with modest reductions in CH₄ and N₂O, reflecting the displacement of fuel combustion in internal combustion engine vehicles. The GHG emission declines exponentially with rate of EV adoption, particularly when electrification is combined with a decarbonized electricity supply. Under the baseline scenario, cumulative emissions reaches 290.3 Mt of CO₂ equivalent (CO₂e) by 2050, reflecting continued reliance on fossil fuels and biomass and limited de-carbonization across sectors. Whereas in transport electrification pathways cumulative emission declines with rate of EV adoptions: 214.5 Mt in moderate and 101 Mt in net zero by 2050, and 150 Mt of CO₂e in ambitious case by 2040, implying transport sector is major source of GHG emission.

These emission mitigation could be achieved only when power supply is from renewable sources. Consequently, The slow adoption yield only modest emission mitigation, whereas high-adoption pathways lead to transformative outcomes, approaching zero emissions for the transport sector by 2050, which cuts nearly 65% of total emissions relative to baseline cases, as shown in Figure 12

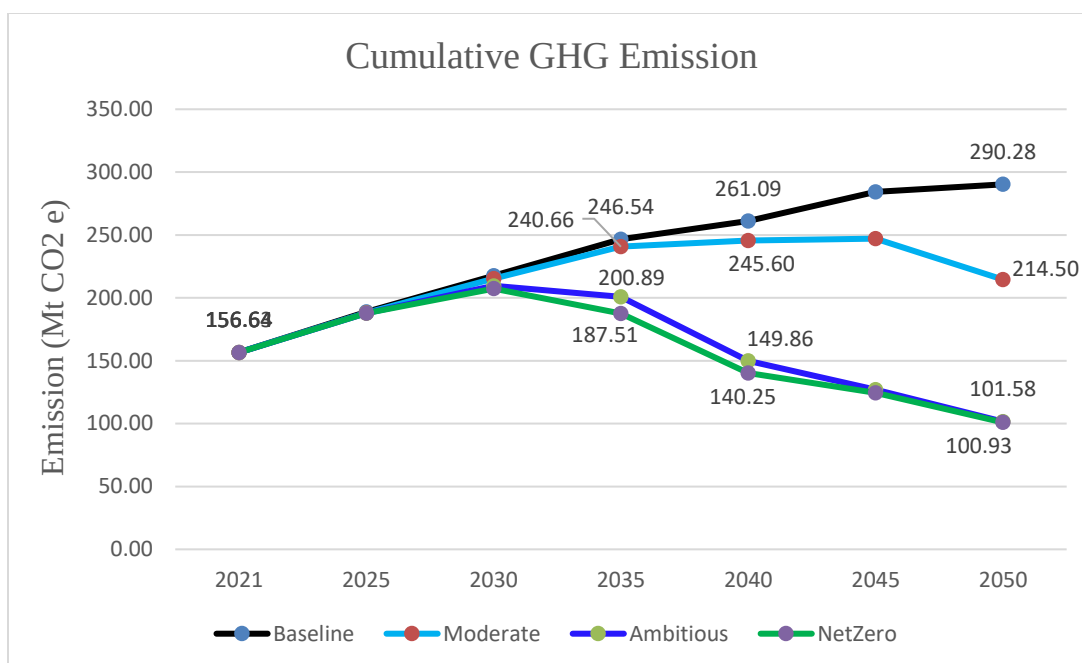


Figure 12: Cumulative emission across scenarios.

When assessed against Ethiopia’s economy-wide NDC targets 141 Mt CO₂e (unconditional) and 71 Mt CO₂e (conditional) by 2035 the emission assessments in this study are slightly higher across all scenarios, reaching 188–247 Mt CO₂e by 2035. Even under the most ambitious pathways, emissions remain above these thresholds, indicating that transport electrification alone cannot achieve national NDC targets within the assessed timeframe. This gap reflects the fact that the NDC targets apply to the entire economy, whereas this study focuses on transport-driven emission dynamics under electrification pathways. The result confirms that EV policies are essential for long-term carbon neutrality in transport, but achieving the conditional and unconditional NDC targets requires coordinated mitigation across all sectors, especially power, industry, and land use.

4.1.4 Economy and Energy Saved

The energy saving assessment indicate that transport electrification delivers substantial long-term energy savings in addition to reducing greenhouse gas emissions, confirming vehicle electrification as a key strategy for improving energy efficiency and supporting de-carbonization in the road transport sector. Figure 13 illustrates the evolution of transport energy demand under alternative electrification pathways. Under the Business-As-Usual (BAU) scenario, total transport energy consumption increases steadily, reaching approximately 323TWh by 2050, driven by

continued reliance on inefficient internal combustion engine (ICE) vehicles and sustained growth in mobility demand.

With the rate of EV adoption across pathways, total transport energy demand declines despite rising transport activity 242TWh, 102TWh and 85TWh by 2050 in moderate ,ambitious and net zero, and 108TWh by 2040 in ambitious scenarios. These energy saving reflects the higher efficiency of electric vehicle drivetrains balances demand growth and improved system utilization. Figure 14 presents cumulative energy savings across adoption pathways and relative to BAU. While transport energy demand continues to rise under BAU, the moderate pathway achieves energy savings of approximately 81TWh by 2050 in relative to BAU. The fast EV adoption delivers substantially larger savings, about 106TWh in ambitious electrification pathway, and the net-zero scenario yields the highest benefit, with energy savings of approximately 129TWh by 2040 compared to BAU. Comparing with the moderate pathway, the net-zero scenario provides an additional 157TWh of savings, confirming that deeper electrification results in larger reductions in final transport energy demand.

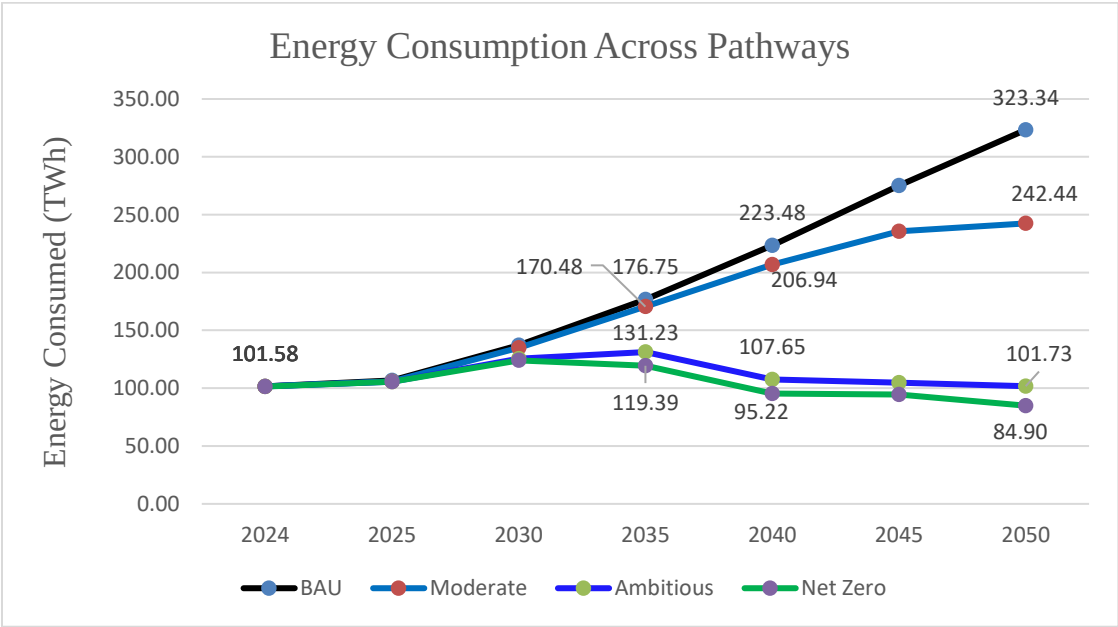


Figure 13: Transport energy consumption across Scenarios

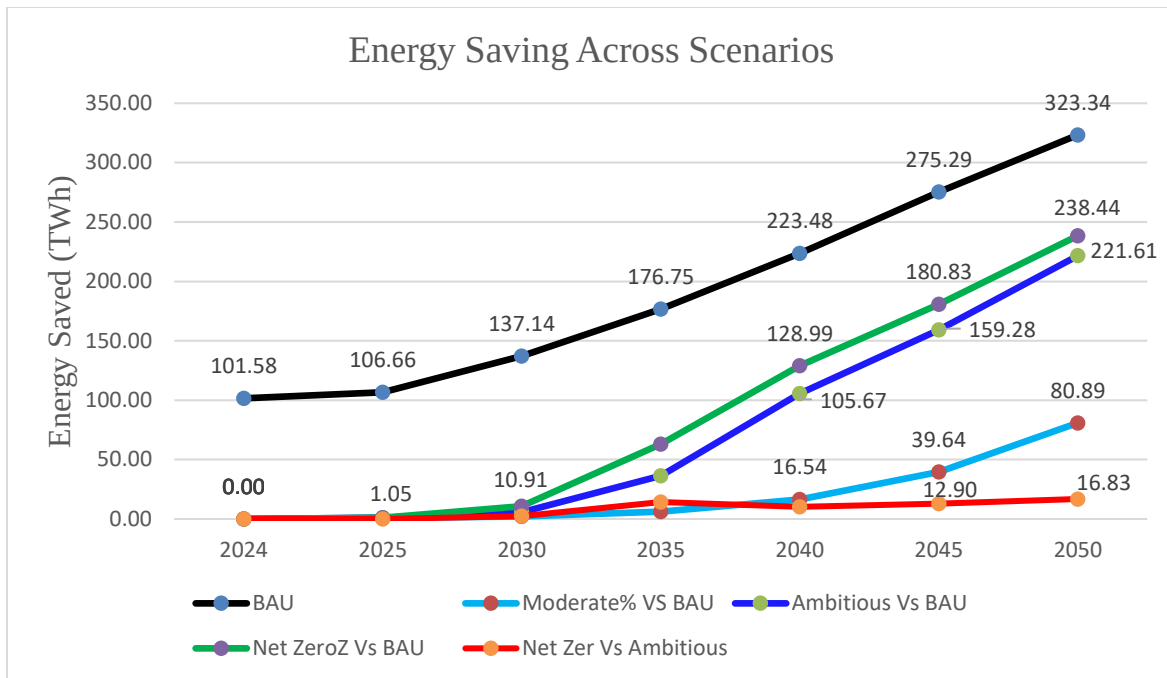


Figure 14: Energy saved across scenarios

Economic saving presents the monetary value of energy savings follow a similar accelerating trend with higher EV penetration. The transport operational costs are strongly driven by the number of fuel consuming vehicles and their associated maintenance requirements. Under the Business-As-Usual (BAU) scenario, operational costs increase sharply, reaching \$51.3 billion by 2050, reflecting the transport vehicle growth with the continued dependence on imported fuels, low energy efficiency, and high maintenance costs of the continued ICE vehicles as shown in Figure 15

Electrification pathways generate increasing economic savings, particularly after 2030, as fuel expenditures and maintenance costs are progressively declined Figure 16. Relative to BAU, the moderate EV adoption pathway achieves cumulative savings of about \$16 billion by 2050. Higher penetration pathways yield larger benefits: the ambitious electrification scenario delivers savings of approximately \$18.25 billion by 2040, while the net-zero scenario saves about \$ 43.8 billion by 2050 in relative to transport baseline cases and \$28 billion in comparison to moderate adoption pathway within the same year.

The combined energy and economic results demonstrate that deeper transport electrification delivers strong economic benefits, driven by the superior efficiency of EVs significantly reduces total energy consumption, and with their lower maintenance. Although electricity generation

requirements increase, the superior efficiency of electric drivetrains and lower operating and maintenance costs dominate system outcomes. These synergistic effects reinforce the emissions results, confirming that high electrification pathways simultaneously enhance energy efficiency, economic resilience, and long-term de-carbonization.

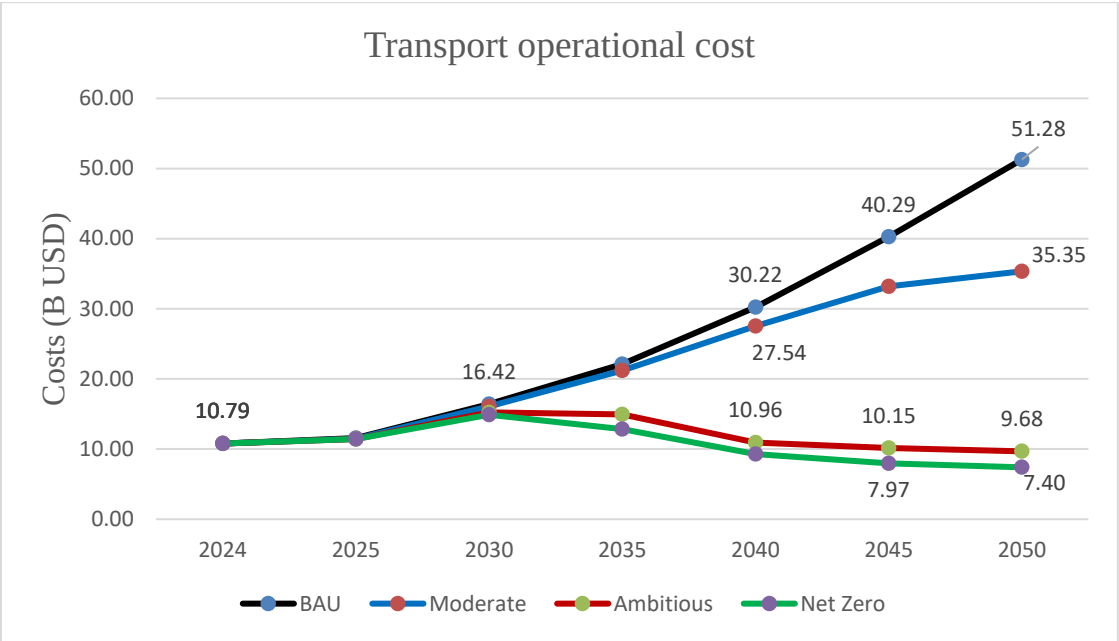


Figure 15: Operation costs across scenarios

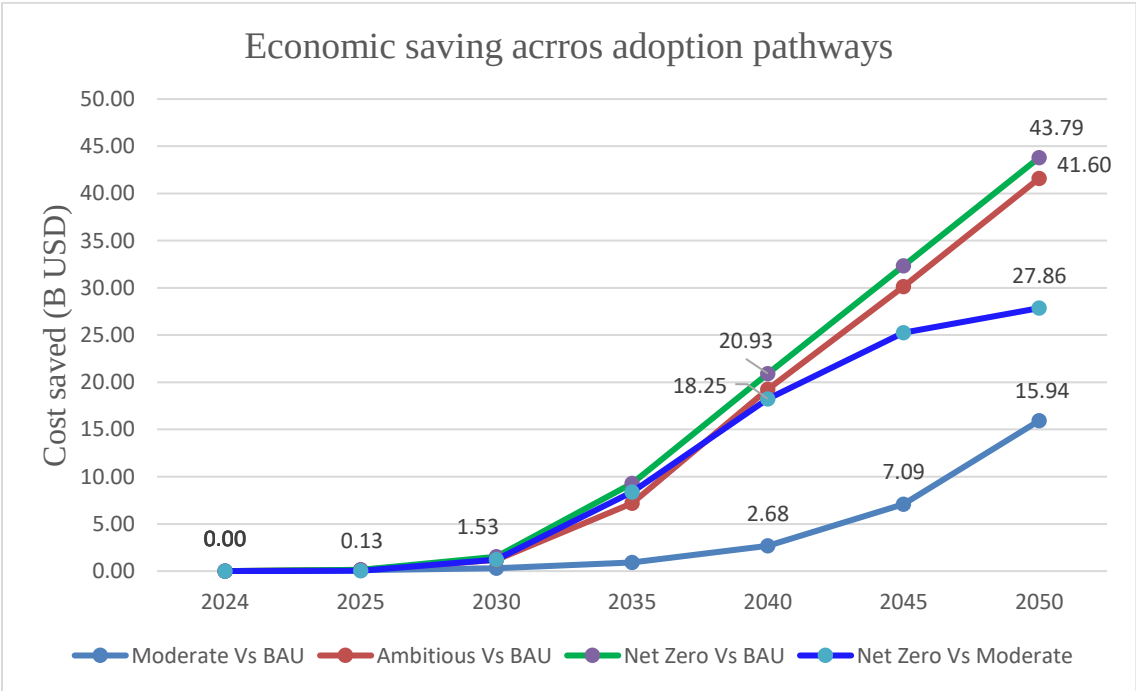


Figure 16: Transport operational cost saving across scenarios

4.2 Integrated Result Discussion

The results indicates that transport electrification pathways integrated with transport demand growth provide policy actionable insights for energy system expansion and the corresponding emission mitigation. The vehicle ownership from Gompertz diffusion pattern, rises from 10 in 2024 to 40 by 250 reflecting Ethiopia's motorization is in pre-transition (convex) trajectory. From the rate of vehicle ownership the road transport demand is projected, grows steadily driven by population growth and urbanization, with vehicle fleet increasing from 1.55 million in 2024 to 4.92 million by 2050, along with the population growth approaching 250 million.

Thus, the continued such road transport fleet expansion and population growth with urbanization derives higher mobility, providing a critical basis for assessing long term energy requirement, investment needs and emission mitigation trajectories under plausible electrification pathways, to support achievement of climate commitment targets

Within these context the three plausible road electrification pathways designed, which are supported by government policy and climate goals by mid-century. The baseline case exhibit the increasing EVs number is due to the total transport fleet size expansion rather than transition to EV technology, thus EVs share remain constant (1.02%) in 2050. In contrast the EV adoption pathways a gradual and fast transition exhibited across pathways attracted by each adoption targets as seen in Figure 7. The ambitious and net zero pathways EV uptake accelerated during 2030 - 2040 and approaching near saturation after 2045 reflecting s-curve, this non- linear diffusion emphasize role of policy credibility , development of power sector expansion and charging infrastructure.

Energy system implications and investment

The examined transport demand growth modeled its electrification pathways embedded within baseline economy-wide system, reveals significant reshaping in capacity expansion and generation mix, which remain adaptable in Ethiopia's renewable-rich power resources. The total capacity must scale from 150 GW in baseline case to 175 GW by 2050 in higher (Ambitious & net-zero) electrification pathways, with capacity addition of 25 GW from baseline case for EV charging demand onward to 2050, whereas only 12.64GW capacity addition is required for moderate pathways in the same year. The capacity expansion of 150 GW for economy-wide system in base line case is driven by demand growth due to population growth and income-driven urbanization.

Such rapid capacity expansion exhibited after 2035 where EV uptakes accelerated as seen from Figure 8 & Figure 9. The generation mix continued to be fulfilled by renewable technologies, with hydropower maintaining foundational role of 43.6% contribution followed by solar and wind more than 16% from each, geothermal 17%, while nuclear contributes 6% in higher electrification pathways for system adequacy and stability. From simulation result of OseMOSYS, in higher road electrification pathways about 426TWh required by 2050 including the economy-wide demand in base line case relative to without EV adoption case of 301.5TWh in the same year. Significant electricity generation of 199TWh is required to achieve the government ambitious transport electrification by 2040 relative to 125TWh in economy wide demand in baseline at the same year, and 135TWh for moderate adoption pathways. Therefore, to meet higher electrification pathways the wind must contribute 60TWh, solar 56.6TWh and 63.8TWh from geothermal starting from third decades see Figure 9. These generation mix translate in to rising annualized investment requirement: from \$42 billion in baseline case to \$52.6 billion in moderate, 64.2 billion in higher EV adoption pathways by the year 2050.

However, due to rapid adoption of EV by 2040 (ambitious pathway) the investment requirement for generation assets nearly the same with the net-zero, reaches \$21 billion in 2040. The capacity expansion and investment requirement for transmission and grid distribution are excluded due to limitation of data, and also demand for the current corridor illuminations.

Emissions and alignment with NDC targets

Road electrification produce substantial GHG mitigation by CO₂ reduction, with smaller but consistent declines in CH₄ and N₂O. Emission decrease non-linearly with penetration of EVs approaching near zero from transport sector by 2050 in full electrification pathway. Cumulative transport emission fall from about 290Mt of CO₂e under BAU in 2050 to 214Mt of CO₂e under moderate and to 102Mt of CO₂e under ambitious pathways, exhibiting that the transport sector is major source of the GHG emission. The net-zero adoption combined with decarbonized power supply mitigate emission to ~101Mt of CO₂e by 2050, which cuts 65% of the emission from BAU in the same year.

However, when benchmarked against Ethiopia's NDC targets 141Mt of CO₂e unconditional and 71Mt of CO₂e conditional by 2035, all adoption pathways remain above target levels ranges 187-246.6 Mt of CO₂e across pathways. This shortfall is due to that NDC targets are economy –wide,

whereas this study focuses only transport driven dynamic within a broader energy system. Overall the result indicates that transport electrification play a major role but not sufficient for achieving NDC target alone by 2035; coordinated mitigation across energy supply, industry land use system is required.

Energy and economic Savings

Despite the increasing electricity demand with are of EV adoption, road electrification yields strong energy-efficiency gains due to superior EV drivetrain performance. Total transport energy demand grows with fleet size expansion reaching up to 323TWH by 2050 under transport baseline case, which is driven by the continued reliance on inefficient internal combustion engine (ICE) vehicle. This energy demand falls to 242TWh in moderate pathway and to 85TWh in net zero pathway by 2050, and with 108TWh energy demand by 2040 in ambitious pathway. A significant energy saving (202TWh) exhibited in net zero pathway by 2050 in relative to baseline case and the ambitious pathways also shows larger saving of 106TWh by 2040 compared to baseline case, while the moderate pathway saves 81TWh by 2050.

These efficiency gains translated in to substantial economic benefits, as a result reduced transport operational cost of EVs, declined from \$51 billion under transport baseline case driven by fuel costs and higher ICE maintenance requirements to ` \$35 billion under moderate electrification and fall to \$9.7 and \$7.4 billion under ambitious and net zero pathways respectively by 2050. EVs adoption deliver significant cost saving through reduced fuel expenditure and lower maintenance cost. The saving across EV adoption pathways are \$16, \$41.6 and \$43.8 billion in moderate, ambitious and net zero in comparison to transport baseline case. These saving dominate system outcomes despite higher electricity generation investment requirement, indicating that self-reinforcement to partially offset the capacity expansion costs favored by deep transport electrification.

Overall, the analysis demonstrate that while transport electrification increase electricity generation requirement, the superior efficiency and lower operating costs of electric vehicles dominate long-term outcomes. Deep transport electrification aligned with renewable based power supply delivers synergetic benefit in energy saving/efficiency, long run emission mitigation, and substantial operational cost reduction. While high adoption pathways can effectively decarbonize road by

mid-century, meeting national NDC targets in the medium term requires integrated, cross-sectoral action. The magnitude of benefit are highly dependent to the rate EV diffusion and the carbon intensity of electricity supply, implying alignment of robust strategy for decarbonizing Ethiopia's road transport sector.

4.3 Key Findings

The finding demonstrate that deep transport electrification fundamentally transform Ethiopia's energy-transport nexus. EV evolution increase electricity demand but simultaneously reduces total energy consumption, emission, and long-term operational costs. The results present quantitative evidence that accelerated EV adoption supported by renewable based electricity supply is essential for meeting climate targets and energy and economic saving gains.

1. Persistent transport demand growth renders road electrification crucial.

The study presents evidence for continued growth of road transport demand and projected to rise significantly from 1.55 million vehicles in 2024 to 4.92 million by 2050, driven by population growth and urbanization. The pre-transition (convex) motorization trajectory described by Gompertz diffusion pattern indicates that the country below saturation, implying continued growth in mobility demand even with slow growth rates. Consequently, emission reduction strategies cannot rely on demand stabilization; instead emission mitigation must achieve alongside rising transport activity, making electrification structurally necessary.

2. Transport electrification reduces total energy demand despite increasing electricity consumption.

While transport electrification increase the electricity demand for EV charging, it significantly reduces total final energy consumption due to higher drivetrain efficiency. Transport energy demand declines from 323TWh by 2050 in BAU case substantially under electrification pathways to 243TWh in moderate, 102TWh in ambitious and 85TWh in net-zero pathways. The net-zero pathway shows significant energy saving of 202TWh in relative to BAU that is about 72% energy efficiency gained. However, electricity demand from EVs adoption follows a non-linear trajectory, with modest increment of nearly 30TWh in all pathways before 2035 and accelerated significantly exceeding 200TWh thereafter as penetration deepens across pathways. This confirms that deep electrification decouples energy consumption from mobility growth, with energy savings increasing proportionally to EV penetration levels and enhances energy security.

3. Power system expansion grows faster with rate of EV adoption

The power expansion grows significantly with rate of EV adoption, it scale approximately from 150GW in baseline case to 175GW by 2050 in high EV adoption pathways. The capacity expansion requirement across adoption pathways grows faster after 2035 with capacity addition more than 12GW to 25GW onward to 2050, it is integrated within economy-wide already growing demand driven from population growth and urbanization. The EV adoption reinforces toward a clean energy system, where the power expansion configuration predominately renewables (hydropower, wind, solar and geothermal) with minor capacity addition from nuclear to satisfy system adequacy and stability for EV adoption embedded within economy-wide sector.

4. Road electrification significantly reduce emission but insufficient to meet NDC target alone

EVs adoption delivers significant, non-linear emission mitigation, by 2050 cumulative transport emission drops from 290Mt CO₂ e in baseline case to 101 Mt CO₂ e in net-zero. The emission mitigation shows huge because each EV replaces a less efficient internal combustion engine vehicle, and the power supply system is renewable, leading to an emission mitigation per EVs exceeds its share of the fleet. However, the emission mitigation EV adoption pathways in this study doesn't meet national NDC targets set by 2035, 141 Mt unconditional and 71Mt conditional, demonstrating that transport electrification alone cannot achieve national climate goals. This shortfall reflects that NDC targets is economy-wide emission coverage due to continued reliance on fossil fuel and biomass consumption, implying the need for cross-sectoral mitigation is essential.

5. Large-scale EV adoption partially offsets additional power expansion investment needs

Transport electrification yields substantial economic benefits while imposing a huge power demand after 2035. Cumulative saving from reduced fuel import and lower maintenance cost of EVs reaches nearly \$43.8 billion by 2050 in net zero pathways, which partially offsets the generation investments (64.2 billion) required for EV adoption. The incremental capacity addition required for EV charging ranges 12 – 25 GW across EV adoption pathways, which grows from 150GW in baseline economy-wide cases to 175 GW in high adoption pathways driven within broader economic growth. Crucially, in high EV adoption (ambitious & net zero) pathways directly determine long-term investment needs and planning horizons, including timing of grid reinforcement and modernization, charging infrastructure rollout, and capacity expansion. Deep

electrification is economically advantageous and technically manageable, provided long-term alignment with accelerated adoption phases.

4.4 Study Limitation and Future Research

This study employs a long-term deterministic modelling framework and therefore does not explicitly represent hourly charging behavior, peak electricity demand, distribution network constraints, or operational grid dynamics. And also due to limitation of reliable data the capital investment requirement for transition and distribution network was not addressed. EV adoption and electricity demand projection are based on policy-consistent assumptions regarding technology (EV affordability), vehicle utilization, and technology performances, which remain subject future uncertainty. Although, uncertainty was addressed through alternative electrification pathways as sensitivity analysis, future studies could incorporate stochastic modelling, higher temporal and spatial resolution, charging behavior analysis, and broader socioeconomic assessment. Nevertheless, the consistency of the result across multiple validation approaches and scenario pathways indicating that the main findings remain robust for strategic energy and transport planning purposes

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study assessed the long-term impact of transport electrification on Ethiopia's energy system under increasing mobility demand driven by rapid population growth and urbanization. By integrating a heterogeneous vehicle fleet representation, policy-based EV diffusion pathway, and OSeMOSYS-based energy system optimization framework, the analysis provides one of first Ethiopian specific integrated assessment of how EV evolution influences electricity demand, power system expansion, investment requirement, GHG emission mitigation, and economic outcome between 20205 and 2050.

The finding demonstrate that Ethiopia's transport sector remain in early motorization stage, with vehicle ownership projected increase from 10 vehicles per 1000 inhabitants in 2024 to 40 vehicles 1000 inhabitants by 2050. Consequently, the total vehicle fleet is expected to expand from 1.55 million in 20204 to 4.92 million vehicles by 2050. This persistent growth in mobility demand indicates that future emission reduction cannot rely on transport demand stabilization but must be achieved through structural transformation of transport technologies, rendering transport electrification as strategic decarbonization pathway.

The analysis confirm that transport electrification fundamentally reshapes the transport-energy nexus. Although EV adoption increase electricity demand and requires additional generation capacity expansion, it substantially improves energy efficiency and reduces overall transport energy consumption. Under transport Business-As- Usual (BAU) pathway, transport energy demand reaches 323TWh by 2050, whereas electrification pathway reduce demand to 242TWh under moderate transition , 102TWh in ambitious and 85TWh in net-zero pathways. Cumulative energy saving reaches 238.5TWh by 2050 under net-zero electrification pathway, demonstrating that mobility growth can be effectively decoupled from final energy consumption through technological transition.

At energy system level, transport electrification accelerates power sector expansion but remains compatible with Ethiopia's renewable energy development trajectory. Total installed capacity increase from 150GW in the economy-wide baseline to nearly 175GW under transport net-zero

electrification pathway by 2050, requiring an additional 25GW of generating capacity to accommodate EV charging demand. The resulting electricity supply remains overwhelmingly renewable, dominated by hydropower, solar, wind, and geothermal resources, with limited contribution of from nuclear power bioenergy to enhance system adequacy and flexibility. These finding indicates that transport electrification can be achieved without compromising Ethiopia's long-term low-carbon power sector transition.

From an economic perspective, transport electrification generates substantial system-wide benefits. Reduced petroleum imports and lower operating and maintenance cost produce cumulative saving of \$16 billion under moderate transition, and \$43.8 billion under net-zero pathway by 2050. Although, net-zero electrification pathway requires additional power sector investment of \$64.2 billion by 2050, a significant share of this cost is offset by long-term operational savings, improving energy security and reducing fuel import dependency.

Environmentally, transport electrification delivers significant emission mitigation but insufficient to meet national climate ambition. Transport sector emission decline from 290 MtCO₂e under BAU to 214 MtCO₂e under moderate transition pathway and 101 MtCO₂e under net-zero pathways by 2050, representing an emission reduction of 65%. However, despite this substantial mitigation, all scenarios remain above the national NDC targets by 2035. This finding highlights that while transport electrification is key component of Ethiopia's de-carbonization strategy, it is not sufficient on its own and must be complemented by mitigation measures across sectors energy supply, industry, agriculture, land-use.

Overall, study concludes that deep transport electrification is technical manageable, economically advantageous, environmentally essential for Ethiopia's long-term development pathways. The results demonstrate that EV adoption can simultaneously enhance energy efficiency, reduce fuel import dependency, improve economic performance, and substantially lower transport sector emissions while supporting a renewable –based electricity supply system. More importantly, the analysis shows that the timing and scale of future EV adoption directly influence electricity demand growth, capacity expansion requirement, and investment needs. Therefore, maximizing the benefits of transport electrification requires coordinated planning between transport and energy sector, proactive expansion of renewable electricity supply and charging infrastructure, and alignment of EV deployment strategies with broader national climate and development objectives.

The modelling framework developed in this study provides quantitative evidence base to support such integrated policy design and long-term investment planning alignment across sectors.

5.2 Recommendation

Since this study provide one of the first quantitative, system-integrated assessment of transport electrification in Ethiopia, connecting fleet size expansion and diffusion, energy system planning, emission mitigation and associated operation costs requirements, the following recommendation are derived directly from the study's empirical findings. The results present strong quantitative evidence supporting policy based deep EVs adoption as key influencing factor low carbon development strategy.

1. Align EV adoption targets explicitly within national energy planning framework

EV deployment target should be explicitly embedded within long term energy system planning frameworks. Given the non-linear increase in electricity demand, particularly after 2035, coordinated planning is essential to avoid supply–demand mismatches, optimize capacity expansion, and ensure cost-effective system development.

2. Prioritize high-penetration electrification pathways supported by renewable expansions

The result shows that deep electrification delivers significant benefits on emission mitigation, energy saving, and economic returns. Therefore, policy maker should prioritize high EV adoption targets aligned with renewable energy system expansion of solar, wind, geothermal and nuclear to sustain a low carbon electricity supply, which reduces emission by 65% compared to baseline case. This coordinated expansion ensures supply adequacy, limits exposure to hydrological variability, and maintain a low-carbon supply mix.

3. Leverage fuel import savings to finance energy transition and accelerate charging infrastructure deployment

Economic saving from reduced petroleum import and lower vehicle operating costs should be formally recognized as a financing offsets for renewable generation expansion and EV charging infrastructure deployment. Policy maker should establish institutional mechanism to earmark avoided fuel import expenditure for reinvestment in power generation sector, thereby

strengthening financial sustainability. Simultaneously the success of EV adoption depends on reliable and accessible charging infrastructure, requiring strategic investment in urban center, transport corridors, and public transit systems, complemented by grid modernization and smart charging solutions to optimize load management and minimizing grid stress.

4. Implement cross-sectoral de-carbonization strategies to achieve NDC targets

The transport electrification alone cannot meet national climate targets, Ethiopia must adopt a cross-sectoral de-carbonization strategy. This includes accelerating power sector, improving industrial efficiency, and ensuring alignment between sectoral actions and economy wide emission mitigation goals.

Annexes

Annex I. Road transport fleet dynamics

Table 2: Road transport fleet and activity data in Ethiopia 2024/2025.

No	Vehicle Type	Fuel type	Activity factor (km/yr)	Quantity	Load factor (p/v) (t/v)	Energy intensity (MJ/km)	Emission Activity ratio C ₂ O (Mt/PJ)	Maintenance Cost per vehicle (\$)	Price of Energy (Fuel/ Electricity) (\$)
1	Buses Seat capacity >12	Diesel Buses	83426	104428	72	7.53	0.480964	15016.68	Gasoline =0.79 Diesel =0.751 Kerosene=0.75 https://www.globalpetrolprices.com/Ethiopia/ Electricity= 0.0382 Collected data
		Electric Buses	83426	257	72	3.3		9010.01	
2	Mini-Buses Seat Capacity <12	Diesel Buses	30000	49613	12	3.51	0.240108	3153.96	
		Gasoline	30000	33076	12	2.85	0.20805	1558.5	
		Electric Buses	30000	8	12	0.69		3153.96	
3	Car (Automobile , Pickup & Ambulance) Seat Capacity <5	Diesel	22043	215181	4	2.95		813.8276	
		Gasoline	22043	290246	4	2.15	0.20805	813.8276	
		Electric	22043	15374	4	0.55	0.237864	469.5159	
4	Motorcycle and Auto rickshaws	Gasoline	18000	539040	3	1.21	0.092418	200	
		Electric	18000	179	3	0.2		100	
5	Truck	Diesel	68730	299250	20	10.52	0.577456	7013.278	
		Electric	68730	24	20	3.5		2808.308	

Annex II. Energy and related data

Table 3: Ethiopian energy resources and related data used in this study

Power Technology	Resource Exploitable potential (GW)	Installed Capacity (GW)	Operational life (years)	Capacity factor	Capex escalation/decline factor/year
Hydropower plant	45	4.82	60	0.25 - 0.50	-1%
Geothermal power plant	10	0.0073	30	0.75	-0.12%
Onshore wind power plant	40	0.404	25	0.17	-10%
Solar PV power plant	70	0.0245	25	0.2	-7%
Biomass plant	2955	0.025	30	0.8	-3%
Off-grid Solar			25	0.2	-7%
Nuclear			60	0.85	
Off-grid diesel			20	0.4	+10%

Annex III. Summary of Assumptions

Parameters	values	References
Saturation of Vehicle ownership	40	Low income economies-21 th century- Assumption
GDP per capita I(t) growth rate	0.049	World Bank -2024 https://data360.worldbank.org/en/indicator/WB_WDI_NY_GDP_PCAP_KD_ZG?view=trend&country=ETH&average=WLD ,
Fuel prices increments rate	0.03	IEA-2024 report
Grid electricity price increments rate	0.0095	EEU-2025 collected data
EV battery pack prices (\$/KWh)	100	Bloomberg-NEF https://battery-tech.net/battery-markets-news/global-lithium-ion-battery-costs-fall-8-to-108-kwh/ ?
Battery discount rate (r),	0.08	Bloomberg-NEF https://battery-tech.net/battery-markets-news/global-lithium-ion-battery-costs-fall-8-to-108-kwh/ ?
Battery amortization period (N) in years	8	Typical battery lifetimes

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