

# Integration of COMSOL Multiphysics Simulation Models into Energy Auditing for Quantifying Energy Savings

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**Abstract** - Energy efficiency has become a major concern for industries and commercial buildings due to rising energy demand and increasing operational costs. Traditional energy auditing methods lack predictive capabilities for evaluating the impact of energy conservation measures. This study proposes a simulation-assisted energy auditing framework that integrates multiphysics modeling in COMSOL Multiphysics with conventional energy audit techniques. The methodology involves data collection through an energy audit, the development of simulation models representing thermal, electrical, and fluid-flow phenomena, and the evaluation of multiple energy-efficiency scenarios. The proposed approach enables accurate prediction of energy savings and financial indicators such as return on investment (ROI) and payback period. A case study of an energy-intensive system in a building environment is analyzed to demonstrate the effectiveness of the proposed framework. The results show that simulation-assisted auditing significantly improves the accuracy of energy savings estimation and provides reliable decision support for implementing energy efficiency measures. The proposed method offers a practical tool for industries and energy managers to optimize energy consumption and improve economic feasibility before implementing energy optimization strategies.

**Keywords** - Energy Auditing, Multiphysics Simulation, COMSOL Modeling, Energy Efficiency, Return on Investment, Sustainable Energy Systems.

## 1. INTRODUCTION

Energy consumption in industrial and commercial sectors has increased significantly over the past decade. Efficient utilization of energy resources has become essential to reduce operational costs and environmental impact. Energy auditing is widely used to analyze energy consumption patterns and identify opportunities for improving efficiency. Several studies have demonstrated the effectiveness of energy audits in identifying inefficiencies in heating, ventilation, and air conditioning (HVAC) systems, lighting systems, and electrical equipment [1,2].

Traditional energy auditing techniques rely on utility data, equipment specifications, and manual measurements. Although these methods help identify inefficiencies, they often lack predictive capabilities for evaluating the impact of energy conservation measures under varying operational conditions. Recent advancements in computational modeling have enabled the use of simulation tools for analyzing energy systems. To overcome these limitations, researchers have increasingly adopted simulation-based approaches that combine numerical modeling with traditional energy auditing methods. Finite element and multiphysics simulation tools have been widely applied for analyzing energy systems and improving system performance. Multiphysics simulation platforms such as COMSOL Multiphysics allow engineers to model complex interactions between thermal, electrical, and fluid flow phenomena [3]. Integrating such simulation tools with energy auditing can provide a predictive framework for evaluating energy efficiency strategies before implementation. Simulation-based energy analysis has gained attention in recent years due to its ability to predict system behavior under different operating conditions. Various simulation tools have been used for energy modeling, including EnergyPlus for building energy simulation and ANSYS Fluent for fluid dynamics analysis. Despite these advancements, limited research has focused on integrating multiphysics simulation with practical energy auditing and economic evaluation. Most studies either focus on simulation modeling or traditional auditing methods independently. Therefore, there is a need to develop an integrated framework that combines simulation-based analysis with energy audit data to improve the accuracy of energy savings estimation and financial evaluation.

Several studies have explored the use of numerical simulation techniques for building energy analysis. Van Schijndel [4] demonstrated the use of finite element methods to perform detailed building energy simulations, showing that multiphysics modeling can provide more accurate predictions of indoor climate conditions and energy consumption compared to conventional methods. The study highlighted the potential of simulation-based approaches to support energy-efficient building design and operation. Similarly, Sezgin *et al.* [5] developed a comprehensive multiphysics model of proton exchange membrane fuel cells using COMSOL Multiphysics. Their work integrated electrochemical reactions, heat transfer, and gas transport processes to evaluate system performance and efficiency. The results demonstrated that multiphysics simulation can effectively capture the complex interactions occurring within energy conversion devices. Multiphysics simulation has also been applied to renewable energy systems and thermoelectric devices. Luo *et al.* [6] presented a comparative analysis of different multiphysics modeling approaches for thermoelectric generator systems. Their work emphasized the importance of coupling thermal and electrical phenomena to accurately predict device performance and energy output. Such studies highlight the importance of simulation tools for analyzing energy conversion technologies. In recent years, research has increasingly focused on improving building energy efficiency through advanced modeling techniques. Yaoxuan *et al.* [7] investigated thermal management strategies in building energy systems using multiphysics simulation. Their results showed that detailed thermal analysis can identify areas of heat loss and help optimize building envelopes, thereby reducing energy consumption. Similarly, Li *et al.* [8] conducted numerical investigations on heat transfer mechanisms in building envelopes and demonstrated that simulation-based optimization can significantly improve building energy performance.

The integration of simulation tools with optimization techniques has also attracted considerable attention. Bagherzadeh *et al.* proposed a framework that combines building energy simulation with machine learning algorithms to optimize energy consumption in buildings. Their approach demonstrated that predictive models can significantly improve the efficiency of building energy systems while reducing operational costs. Another important application of multiphysics simulation is the analysis of advanced energy storage and thermal management systems. Xiao *et al.* investigated the thermoregulation performance of phase-change materials in building walls using numerical simulation techniques. Their findings indicated that thermal energy storage materials can significantly enhance the energy efficiency of buildings by stabilizing indoor temperatures and reducing cooling loads. Although previous studies have successfully demonstrated the advantages of multiphysics simulation for energy system analysis, relatively limited research has focused on integrating simulation models directly into the energy auditing process.

Therefore, the present study aims to bridge this gap by developing a simulation-assisted energy auditing framework that integrates COMSOL-based multiphysics modeling with traditional energy audit techniques. The proposed approach not only improves the accuracy of energy consumption analysis but also enables quantitative evaluation of energy savings and return on investment (ROI) for different energy efficiency measures. This integration can provide valuable insights for energy managers, engineers, and policymakers seeking to implement cost-effective and sustainable energy solutions.

## 2. METHODOLOGY

This study proposes a simulation-assisted energy auditing methodology that integrates multiphysics modeling with conventional auditing practices to quantify potential energy savings and predict return on investment (ROI) for energy efficiency improvements. The proposed research methodology consists of several stages, including energy audit data collection, simulation model development, model validation, scenario analysis, and economic evaluation. An energy audit is conducted to collect baseline data on energy consumption and operational characteristics. The collected data includes Electricity consumption records, Equipment power ratings, operating schedules, Environmental conditions, and Thermal properties of building materials. Measurement instruments such as power analyzers, temperature sensors, and smart energy meters are used for data collection. A detailed simulation model of the energy system is developed using COMSOL Multiphysics. The model includes geometry, material properties, boundary conditions, and operational parameters. The simulation integrates multiple physics domains includes heat transfer analysis, Fluid flow modeling, and Electrical power analysis. The simulation results are compared with the measured data obtained during the energy audit. Model parameters are adjusted until the deviation between simulated and measured values falls within an acceptable range. Energy optimization scenarios are evaluated using simulation and are focused on improved thermal insulation, efficient lighting systems, HVAC optimization, and High-efficiency motors. The financial feasibility of each energy efficiency measure is evaluated by calculating the payback period and return on investment.

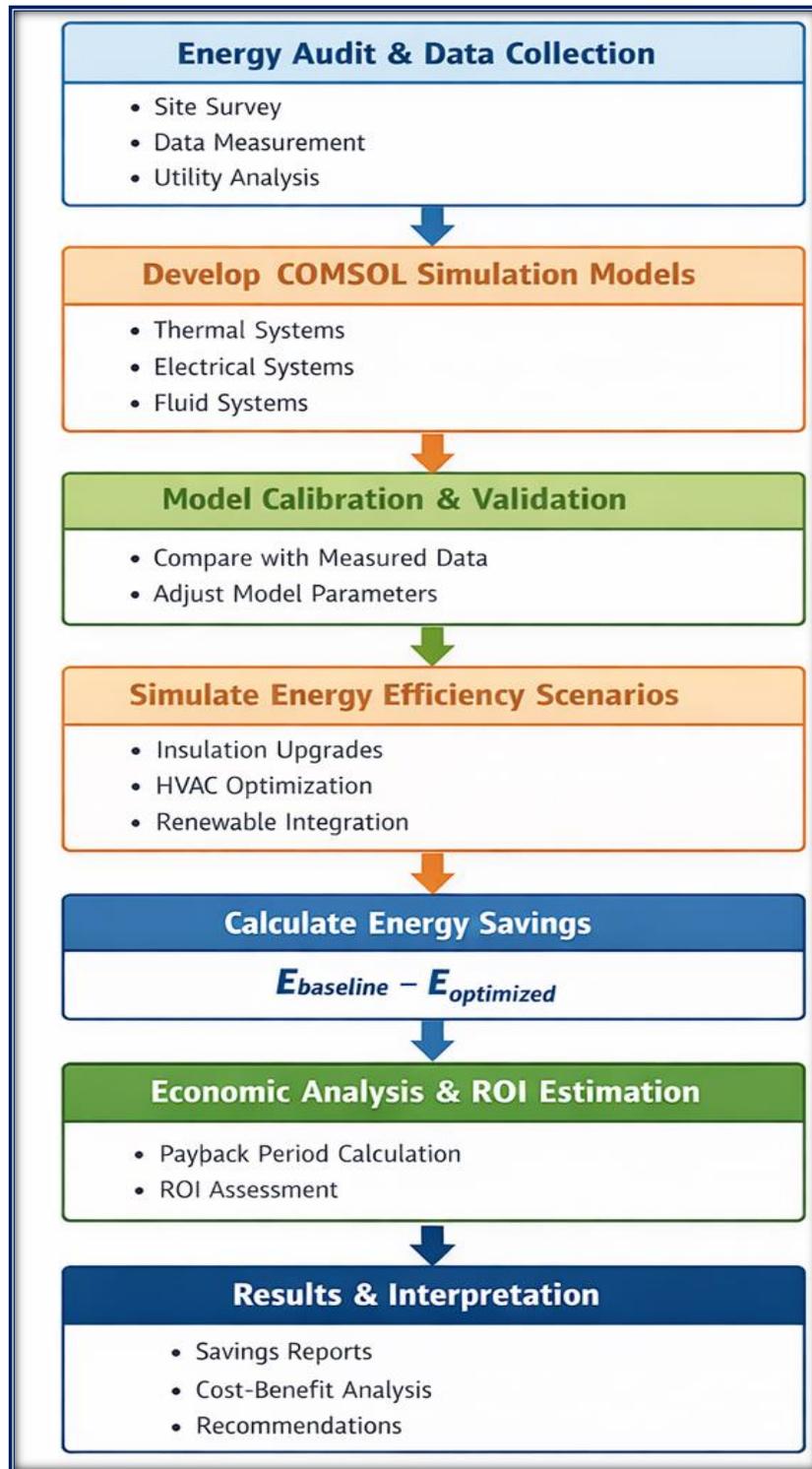


Fig. 1. Adopted methodology to estimate energy saving and ROI.

Energy savings are calculated using the difference between baseline and optimized energy consumption (Fig. 2)

$$\text{Energy Savings} = E_{Baseline} - E_{Optimized}$$

Return on Investment (ROI) is calculated as  $ROI = \frac{\text{Annual Savings}}{\text{Investment Cost}} \times 100$

Payback period is estimated as  $Payback\ period = \frac{Initial\ Investment}{Annual\ Savings}$

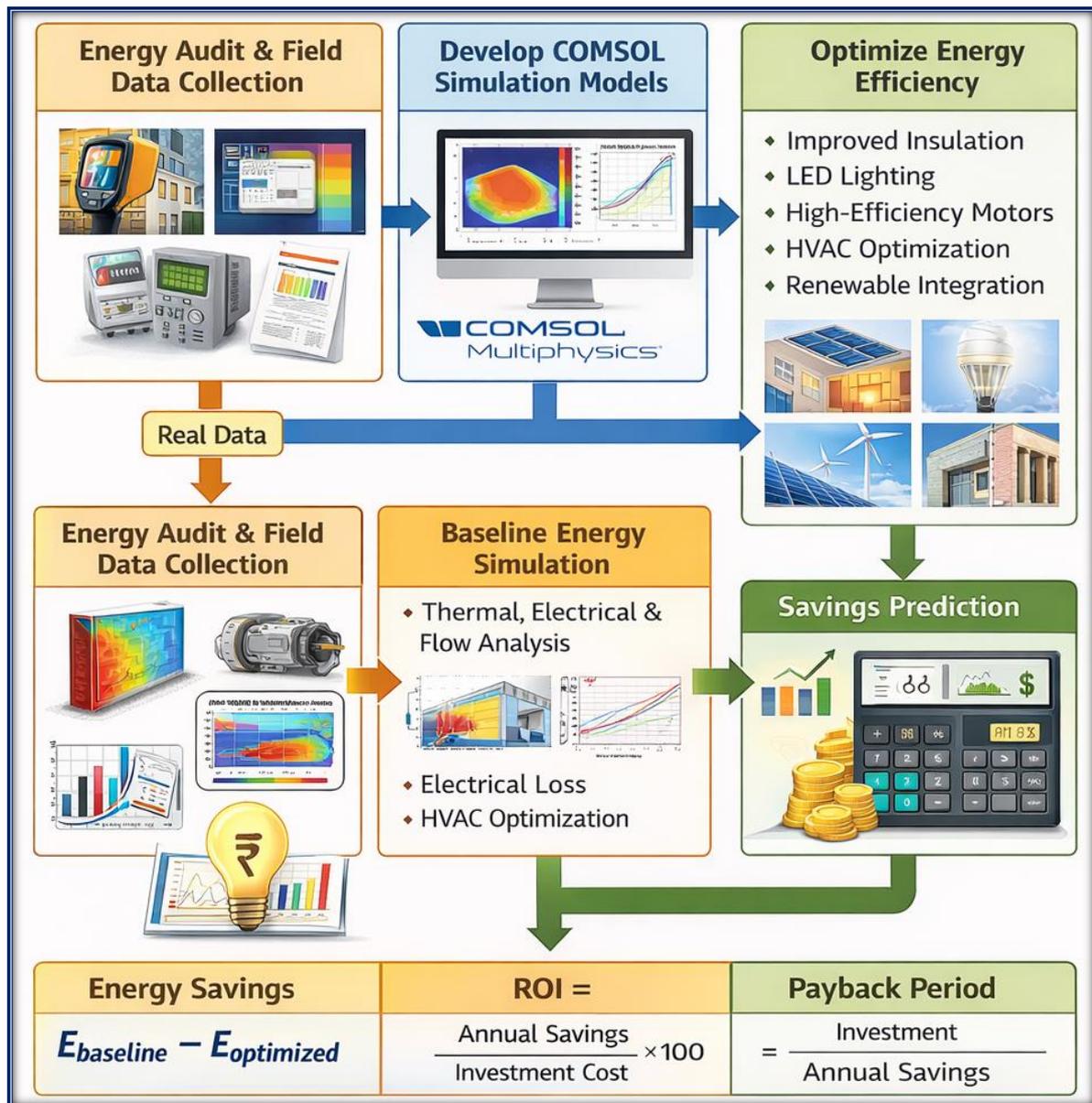


Fig. 2. Procedure adopted to evaluate the ROI of the energy estimation.

A case study is conducted on an energy-intensive system within a commercial building environment. The energy audit identified HVAC systems and lighting systems as the major contributors to energy consumption. Simulation models were developed to analyze heat transfer and airflow within the building. Several energy efficiency scenarios were simulated, including insulation improvements and HVAC optimization. The simulation results showed a significant reduction in energy consumption after implementing the proposed measures.

### 3. RESULTS AND DISCUSSION

The simulation results indicated that integrating energy efficiency measures could significantly reduce energy consumption. Table 1 shows the comparison between baseline and optimized energy consumption.

Parameter	Symbol	Baseline Value	Optimized Value	Reduction (%)	Unit
Total Energy Consumption	$E_{Total}$	250,000	170,000	32.0	kWh/year
HVAC Energy Consumption	$E_{HVAC}$	120,000	90,000	25.0	kWh/year
Lighting Energy Consumption	$E_{light}$	40,000	20,000	50.0	kWh/year
Motor Energy Consumption	$E_{motor}$	60,000	45,000	25.0	kWh/year
Cooling Load	$Q_{Cool}$	30,000	22,000	26.7	kWh/year
Peak Power Demand	$P_{peak}$	85	60	29.4	kW
Average Indoor Temperature	$T_{avg}$	28	24	—	°C
Heat Loss through Walls	$Q_{loss}$	15,000	9,000	40.0	kWh/year
Airflow Efficiency	$\eta_{air}$	65	85	+30.8	%
System Efficiency	$\eta_{sys}$	70	88	+25.7	%

The economic analysis revealed that the proposed energy efficiency measures resulted in a payback period of approximately three years and a significant return on investment. The results demonstrate that integrating multiphysics simulation with energy auditing provides more accurate predictions of system performance and financial benefits.

The proposed approach offers several advantages, such as accurate prediction of energy savings, evaluation of multiple optimization scenarios, improved decision-making for energy investments, and reduced implementation risks. The study is limited by assumptions made during simulation modeling and the availability of accurate operational data. Future research may involve integrating real-time monitoring systems and artificial intelligence techniques to enhance predictive capabilities.

From Table 1., the total energy consumption reduced by ~ 32% validating the effectiveness of simulation-based optimization. Lighting shows highest reduction (50%), mainly due to LED replacement and control systems. HVAC energy reduced by 25%, attributed to improved airflow and thermal optimization. Cooling load reduction (~26.7%) indicates improved heat transfer management. Peak power demand reduced by ~30%, which lowers electricity costs and demand charges. Indoor temperature improved from 28°C to 24°C, enhancing thermal comfort. Airflow efficiency increased significantly, showing effectiveness of CFD-based optimization.

#### 4. CONCLUSIONS

This study presented a simulation-assisted energy auditing framework that integrates multiphysics modeling with conventional energy auditing practices. By using COMSOL Multiphysics, the proposed methodology enables accurate prediction of energy savings and financial feasibility for energy efficiency measures. The case study results demonstrate that simulation-assisted auditing can significantly improve decision-making and reduce uncertainty in energy optimization projects. The proposed framework can serve as a valuable tool for industries and building managers seeking to improve energy efficiency and sustainability.

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