Maximizing Energy Efficiency in Air Conditioning Systems through Mechanical-to-Electrical Energy Conversion Using DC Motors

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Abstract - **This paper explores a novel method for enhancing the energy efficiency of air conditioning (AC) systems by converting the mechanical energy from the external fan into electrical energy using a DC motor. By harnessing this often wasted rotational energy, the system generates usable power, which can be stored and utilized to reduce overall energy consumption. Our experimental setup demonstrates that at typical wind speeds (5-10 m/s), the system can effectively generate power to charge batteries, contributing to potential energy savings. Additionally, a prototype using a smaller fan validated the concept by generating sufficient voltage for charging lightweight devices, like smartphones. The proposed approach offers a scalable and environmentally friendly solution that could be integrated into existing AC units or new HVAC models, providing significant economic and environmental benefits.**

Keywords: Sustainable energy, mechanical energy conversion, air conditioning systems, DC motor energy capture, renewable energy, HVAC efficiency, energy storage.

I. INTRODUCTION

The first of the factors necessary for the normal life and functioning of society is energy. In recent decades, both the increase in population and the rapid development of new technologies have increased the demand for energy consumption manifold. The vast majority of energy sources used, while being natural (oil, gas), cause environmental pollution. Today, measures taken around the world give hope that the global problem will be solved. However, on the other hand, the increase and long-term continuation of conflict zones are an impetus for the sustainable production of such natural resources. In the report presented by the IEA in 2023, it is noted that,"… if governments successfully pursue a 1.5 °C trajectory, and emissions from the global energy sector reach net zero by mid-century, oil and gas use would fall by 75% to 2050." [1].

There is a large amount of material on the open internet resources related to the acquisition and use of renewable energy. The study in [2] aims to examine the literature on the methods for biomass to energy conversion systems design. To this aim, a comprehensive review is conducted to offer a clear vision of the advances in the field. The studies that are reviewed are classified into three categories; review studies about energy systems, the studies about the design of biomass to energy conversion systems and the studies about design of hybrid renewable energy systems that include biomass as an energy source.

Authors presents an energy system analysis methodology and a tool in [3] for the design of renewable energy systems. This includes the results of more than ten comprehensive energy system analysis studies. The large-scale integration of renewable energy into the present system has been analyzed, as well as the implementation of 100 percent renewable energy systems. Second, in terms of politics and social science, how can society implement such a technological change; thus, this chapter introduces a theoretical framework approach, which aims at understanding how major technological changes, such as renewable energy, can be implemented at both the national and international levels. This second aspect involves the formulation of the Choice Awareness theory, as well as the analysis of 11 major empirical cases from Denmark and other countries.

Renewable Energy System comprising solar and wind energy, is an eco-friendly and cost-effective option for powering the rural areas compared to conventional sources. The drawback of these systems is that they are less reliable as the generated power depends on meteorological conditions. A properly designed hybrid renewable energy system (HRES) that combines two or more renewable energy sources, like a wind turbine and a solar system with battery back-up increases the reliability of these systems in standalone mode. Hence, the incorporation and collective utilization of renewable energy sources are becoming increasingly popular fields of research. A comprehensive review of various aspects of an HRES is presented in [4]. This material discusses different

methodologies available in the literature on feasibility analysis, optimum sizing, modelling, control aspects, and reliability issues of the HRES.

In remote area applications, where grid approach is either not feasible or very costly, hybrid energy systems are recommended to supply the electric power needs of single or multiple user utility for household or irrigation applications [5]. In the areas where grids are not connected, electrical power can be generated by solar cells, wind turbine generators, hydro power plants, or diesel engine generators. Multiple sources can be combined to generate the desired electrical energy for remote areas. When the majority of the sources are renewable generating sources, then the combination is known as a Hybrid Energy System.

Authors in [6] developed renewable energy systems isolated or connected to the electric distribution network. Evaluation of autonomous hybrid energy systems from a technical and economic perspective is a difficult problem that requires using complex mathematical models of renewable sources and generators, such as photovoltaic panels and wind turbines, and the implementation of optimization techniques in order to obtain an economically successful design. This paper describes and analyzes traditional isolated energy systems powered by solar PV and wind energies provided with a battery energy storage system. Simulation and optimization are illustrated through the analysis of a rural electrification project in Tangiers (Morocco) in order to provide electricity to rural clinic. Optimization analysis suggests the installation of a PV/BESS system due to the magnitude of the load to be supplied, operating costs, and environmental conditions.

In this article a review has been done on scope of CO_2 mitigation through cookers, water heaters, dryer, biofuel, improved cook stoves and by hydrogen [7].

The global shift towards sustainable energy solutions drives the need for innovative methods to reduce energy consumption and mitigate environmental impacts in everyday appliances. Air conditioning systems, prevalent in residential, commercial, and industrial sectors, are significant energy consumers and contribute to high electricity demand, especially during peak seasons. Therefore, any approach to reduce their energy consumption could offer considerable environmental and economic benefits. The external fan in an air conditioning (AC) unit, often in constant operation, generates mechanical energy that is typically dissipated into the environment without any productive use. This wasted energy presents an untapped opportunity for energy conversion and utilization. The primary objective of this project is to develop a system that harnesses this mechanical

energy and converts it into usable electrical energy, thereby improving the overall efficiency of the AC unit.
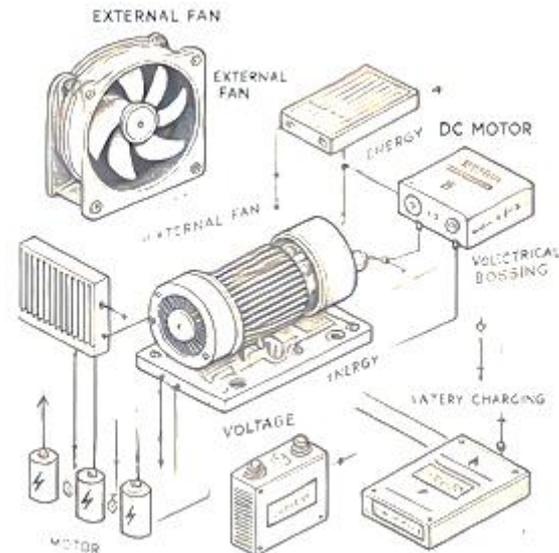

Figure 1: General scheme of the system

This project seeks to attach a DC motor to the fan of the AC's external unit, thereby converting the rotational mechanical energy into electrical energy. This generated energy can then be stored or utilized, potentially offsetting part of the power demands of the AC unit itself or other small devices. This approach not only targets energy efficiency but also contributes to environmental sustainability by reducing reliance on grid power. Given the universal use of air conditioning systems across residential, commercial, and industrial environments, this technology has vast market potential. Developing it as a retrofit kit for existing AC units or integrating it into new models could position this solution as a cost-saving, environmentally friendly option in the HVAC market.

II. EXPERIMENTAL PART

Advances in wireless sensors, biomedical devices, and micro-robotics exert more pressure on creating reliable, miniaturized, and self-sustained energy supply solutions for these micro-electromechanical systems. Rotational energy harvesting (REH) is one of the rapidly growing areas for self-powered electronics using available rotational energy or energy converted from other sources in the environment. This paper comprehensively reviews the state-of-the-art progress in REH in terms of the available energy characteristics, harvester categories, adopted methodologies and mechanisms, and promising applications. Unique mechanisms and methodologies, such as using gravity and centrifugal force combined with other nonlinear mechanisms, are discussed and

characterized. In terms of applications, wearable and implantable devices, automotive, rotating machines, renewable energy systems, and environmental sensing are discussed and reviewed to illustrate how rotational energy harvesters have been developed and adopted accordingly. The key developments, critical challenges, and issues are summarized and discussed based on progress to date. Moving forward, an outlook is presented to outline potential research directions and opportunities in this area [8].

The electricity grid is a complex system in which power supply and demand must be equal at any given moment. Historically, supply has been adjusted to meet changes in demand, from the daily patterns of human activity to unexpected changes such as equipment overloads, wildfires, storms, and other extreme weather events. Now, we also look to flexibility in electricity demand to help optimize use of renewables, from how we heat and cool our homes to when we charge electric vehicles. Energy storage plays an important role in this balancing act and helps to create a more flexible and reliable grid system [9].

Batteries store electricity through electro-chemical processes—converting electricity into chemical energy and back to electricity when needed. Types include sodium-sulfur, metal-air, lithium-ion, and lead-acid batteries. Lithium-ion batteries (like those in cell phones and laptops) are among the fastest-growing energy storage technologies because of their high energy density, high power, and high efficiency. Currently, utility-scale applications of lithium-ion batteries can only provide power for short durations, about 4 hours. Residential storage can last longer depending on the model, size, capacity, and demands of the home.

Batteries can be sited at the generator, along transmission lines, or in the distribution system. They also have a variety of end uses, such as in commercial buildings, residences, and electric vehicles. Advances in lithium-ion battery technologies have been made largely due to the expanding electric vehicle (EV) industry.

The available power from wind can be calculated using the formula for wind power on a turbine:

$Pwind = 0.5 \times \rho \times A \times v3$ $\rho = 1.225 \ kg/m^3$ (Air density at sea level) A = Swept area of the fan blades (corresponding area with 0.4 m diameter: $A = 0.1256 \ m2$) v = Wind velocity (in m/s) With 5 m/s velocity: $Pwind = 0.5 \times 1.225 \times 0.1256 \times 53$ $Pwind = 9.6W$ With high wind velocity($10m/s$): $Pwind = 0.5 \times 1.225 \times 0.1256 \times 103$ $Pwind = 76.8W$.

Efficiency adjustment (Betz Limit): The maximum theoretical efficiency (Betz Limit) for capturing wind energy is 59.3%. Assuming an actual conversion efficiency of 50%

due to losses in the fan and generator system: At 5 m/s wind speed: $Pusable = 9.6W \times 0.5 = 4.8W$ At 10 m/s wind speed: $Pusable = 76.8W \times 0.5 = 38.4W$.

Generator Output (DC Motor as Generator): The motor voltage output is directly related to the rotational speed, given by: $V = k \times \omega$ k motor constant($V/rad/s$) ω rotational speed (rad/s) For a fan rotating at 100 RPM (moderate wind condition): $\omega = 2\pi \times 100 \ 60 = 10.47 rad/s$ Assuming a motor constant $k = 0.5V/rad/s$: $V = 0.5 \times 10.47 = 5.24V$ This voltage is appropriate for charging a 12V battery system when boosted using a DC-DC converter.

Battery Charging and Storage: We estimate using a 12V, 100Ah battery bank. The total energy storage capacity is: $Estored = 12V \times 100Ah = 1200Wh = 1.2kWh$ If the system generates 50W of usable power on average (at 10 m/s wind speed), the time to fully charge the battery is: $t = 1200Wh \ 50W = 24 hours$ This is under ideal conditions, assuming no losses and continuous wind.

Prototype: For the available small fan, wind power calculation is: - Diameter of the fan: 80 mm (0.08 m). - Area: A = $\pi \times (0.04)2 = 0.005 \ m2$. Wind power with different wind speeds: - 5 m/s velocity: 0.192W.

10 m/s velocity: 1.54W According to efficiency calculations, only 50% of this power is converted to electrical energy. The rotational speed of the motor is 1500 RPM and This produces a voltage of 4.71V, which is enough to charge 3.7V lithium-ion batteries. Energy Harvesting and Storage 3.7V, 1000mAh lithium-ion batteries are used to harvest and store energy. The average power of the system is 0.192W at a wind speed of 5 m/s, and it takes about 19.27 hours to fully charge the battery. At a higher wind speed (10 m/s), this power reaches 1.54W, and it takes only 2.4 hours to fully charge the battery. This ensures that the system operates with high efficiency. In our experiment, a wind speed of 20 m/s was applied to the existing 80 mm diameter fan. In this case, the time required for full charging at a speed of 10 m/s with the previous calculation is reduced by 8 times. At the same time, since the volume of the battery we used is 9 times greater than the calculation, the time increases by 9 times. This is approximately 162 minutes. This wind, which we applied at intervals of 1-2 minutes during the experiment, caused the battery to be charged by 1%. This also shows that our calculation works correctly in practice with a small error.

III. RESULTS AND DISCUSSIONS

- Typical energy needed to fully charge a smartphone: ~17.4 Wh
- A prototype battery (3.7Wh) can charge a phone up to 20% once.

▪ The main 12V, 100Ah battery can provide about 69 full charges.

This helps demonstrate that even small amounts of energy harvested from wind can be useful for lightweight devices like phones, but larger systems are required for multiple or continuous charges. Results and Discussion Experimental Outcomes Testing under various wind speeds and fan operational speeds validated that the DC motor could effectively generate a steady voltage. Generated power levels aligned with calculated values for both 5 m/s and 10 m/s conditions, confirming theoretical predictions.

Environmental and Economic Impact: Adopting this approach on a larger scale could meaningfully reduce energy demand from the grid. Our cost analysis suggests that the initial investment could be recouped through energy savings within a few years, especially in areas with high energy costs or frequent AC usage. Comparative Analysis Studies on similar HVAC energy-saving technologies demonstrate that capturing otherwise wasted energy significantly reduces overall energy demand and operational costs. Compared to these solutions, our system offers a practical, self-sustaining power source that integrates directly with existing infrastructure [10-12].

IV. CONCLUSION

Offers Future Applications Beyond air conditioning systems, this technology could apply to other devices with fans or rotational components, such as ventilation fans, outdoor units, and even standalone small wind turbines. Expanding the application scope could enhance the technology's marketability. Product Development Potential Creating a standardized kit for retrofitting various AC models would allow for broad adoption. Additionally, partnering with HVAC manufacturers to incorporate this energy-saving feature in new models could streamline adoption in residential and commercial markets.

REFERENCES

[1] The Oil and Gas Industry in Net Zero Transitions, *IEA, Paris, Licence: CC BY* 4.0, 2023.

[2] S. Yılmaz, H. Selim. "A review on the methods for biomass to energy conversion systems design". *Renewable and Sustainable Energy Reviews*. Volume 25, pp. 420-430, 2013.

[3] H. Lund. "The Choice and Modeling of 100% Renewable Solutions", *Renewable Energy Systems*, pp. 1-12, 2010.

[4] P. Ganguly, A. Kalam, A. Zayegh. "Solar–wind hybrid renewable energy system: current status of research on configurations, control, and sizing methodologies.

Hybrid-Renewable Energy Systems in Microgrids. Integration, Developments and Control". *Woodhead Publishing Series in Energy,* pp. 219-248, 2018.

[5] A. K. Bansal. "Sizing and forecasting techniques in photovoltaic-wind based hybrid renewable energy system: A review". *Journal of Cleaner Production*, Volume 369, 33376, 2022.

[6] J. M. Lujano-Rojas, R. Dufo-López, J. L. Bernal-Agustín, G. J. Osório, J. P.S. Catalão. "Optimum Design of Small-Scale Stand-Alone Hybrid Renewable Energy Systems". *Optimization in Renewable Energy Systems.Recent Perspectives*, pp. 279-306, 2017.

[7] N.L. Panwar, S.C. Kaushik, Surendra Kothari. "Role of renewable energy sources in environmental protection: A review". Renewable and Sustainable Energy Reviews, Volume 15, Issue 3, pp. 1513-1524, 2011.

[8] Fu. Hailing, M. Xutao, D. Yurchenko, Sh. Zhou, S. Theodossiades, K. Nakano, E. M. Yeatman. "Rotational energy harvesting for self-powered sensing". *Joule*, Volume 5, Issue 5, pp. 1074-1118, 2021.

[9] Energy Storage: How It Works and Its Role in an Equitable Clean Energy Future. 2015, *updated* 2021 https://www.ucs.org/resources/how-energy-storage-works

[10] P. Roy, J. He, T. Zhao, and Y. V. Singh, "Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review", *IEEE Open Journal of the Industrial Electronics Society,* vol. 3, pp. 81-104, 2022.

[11] D. Li, S. Wang, and P. Yuan, "A Review of Micro Wind Turbines in the Built Environment", *Asia-Pacific Power and Energy Engineering Conference*, *Chengdu, China*, pp. 1-4, 2010.

[12] Y. Peng et al., "Energy Consumption Optimization for Heating, Ventilation and Air Conditioning Systems Based on Deep Reinforcement Learning", *IEEE Access*, vol. 11, pp. 88265-88277, 2023.

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