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Optimizing energy efficiency and lighting in residential villas: a holistic approach using renewable energy and smart technologies

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Abstract. This article aims to design and analyze energy systems for a villa to address the dual challenges of inadequate illumination and excessive electricity consumption. The study employs specialized software programs, including AutoCAD, PVsyst, DIALux evo, and T*sol, to design and dimension the villa's energy systems. A comprehensive analysis of the photovoltaic system is conducted alongside precise architectural modelling and simulations of the interior lighting and solar water heater system. Additionally, the effectiveness of motion detectors in optimizing interior lighting to reduce energy consumption is examined, and solar lamps are integrated for the villa's exterior lighting to promote sustainability. The findings indicate that the implementation of advanced energy system designs and the use of motion detectors can significantly enhance interior lighting while simultaneously reducing energy consumption by 30%. This paper contributes a holistic approach to energy system design in residential settings, offering innovative solutions for improving lighting quality and energy efficiency in villa architecture. The integration of renewable energy sources and smart technologies underscores the potential for sustainable living solutions in modern residential designs.

1 Introduction

The rising demand for energy-efficient solutions in residential design has emerged as a critical issue, especially with urbanization and population growth [1]. According to a 2023 report by the U.S. Department of Energy (DOE), implementing energy-saving measures in homes can decrease energy consumption by 30% or more. This reduction is achievable through the implementation of cutting-edge technologies such as intelligent thermostats, energy-conserving appliances, and enhanced insulation. Smart home solutions can reduce energy use by 15-25%, equating to large monthly savings and lower CO2 emissions [2]. In addition, current research on energy efficiency in residential structures reveals enormous prospects for reducing energy usage and greenhouse gas emissions. These studies underline

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that renewable energies are vital for boosting energy efficiency and sustainability in residential environments. Homeowners can minimize reliance on conventional energy sources by incorporating systems like solar panels and wind turbines, leading to both financial savings and environmental benefits. A research article by Aste et al. analyzes how photovoltaic systems might be integrated into building materials, such as roofs and facades, to boost energy efficiency while maintaining aesthetic appeal. The study shows the potential of Building-Integrated Photovoltaics (BIPV) systems to supply clean energy and minimize carbon emissions in residential buildings, particularly in the context of European Union laws like the Energy Performance of Buildings Directive (EPBD). The methodology utilized incorporates thorough dynamic energy simulations to analyze the performance of a reference high-performance building. Research that utilizes comparable simulation methodologies to evaluate energy consumption and efficiency in residential buildings might provide useful insights into the effectiveness of various energy-saving measures [3]. The development of sophisticated energy simulation programs such as EnergyPlus has played a pivotal role in enhancing energy efficiency in contemporary structures. These advanced tools facilitate comprehensive evaluation and modeling of a building's energy consumption, contributing to the formulation of strategies to reduce energy usage and mitigate carbon emissions. The integration of these technologies with other innovative approaches further augments their capacity to optimize energy efficiency. Incorporating regression models and sensor-derived data in conjunction with EnergyPlus enhances the accuracy of energy forecasts and facilitates the development of state-of-the-art energy management systems [4]. The software DIALux evo facilitates the modeling and enhancement of both natural and artificial illumination, which is crucial for minimizing energy consumption. By utilizing a three-stage approach for calculating daylight, the program provides more expeditious and accurate assessments, enabling improved coordination between natural and electric lighting. This enhanced integration can result in more energy-efficient lighting designs, thereby reducing the dependence on artificial light sources and consequently conserving energy [5]. PVsyst is recognized as a commonly used simulation software for calculating energy yield and optimizing system design [6, 7, 8, 9]. T*SOL software has been applied to model energy generation for hot water and heating, combining meteorological data and system components for precise simulations. The study evaluated three distinct solar collector setups (Apricus, Thermital, and Eraslan) with various configurations and parameters and identified the Thermital system with an ETC of 3.9 m2, 250 L, and open loop configuration as the most appropriate system, yielding 1223 kWh of energy production, 86% solar fraction, and a potential reduction of up to 1316 kg/year in CO_2 emissions [10]. The incorporation of smart sensors in residential structures greatly boosts energy efficiency and reduces consumption. These systems help reduce energy losses in heating and ventilation by adapting to user needs and thus improving energy efficiency [11]. Smart systems employ sensors to monitor variables like temperature and occupancy and alter settings accordingly. For example, integrating occupancy sensors with automated lighting systems allows for lights to be turned off when rooms are vacant, as stated by Chen et al. (2022) [12]. This article examines the design and analysis of energy systems for a villa, tackling three significant issues: insufficient lighting, water wastage and excessive energy use. These problems adversely affect the comfort and utility of living environments in the villa while also exacerbating energy waste and environmental damage [13, 14]. To address these difficulties efficiently, we will employ a range of specialist software tools, including AutoCAD, PVsyst, Dialux Evo, and T*sol. These programs enable a holistic approach to the design and sizing of the villa's energy systems, allowing for an in-depth analysis of the photovoltaic system, accurate modeling of architectural components, and simulations of interior lighting and solar water heating systems. This study will examine the effectiveness of motion detectors in enhancing indoor lighting. Through the integration of these technologies, we intend to substantially decrease energy usage while improving the quality of illumination [15]. The deployment of solar lamps for outdoor lighting will be evaluated as a sustainable and economical alternative, enhancing the villa's overall energy efficiency strategy. This study aims to present a comprehensive solution that enhances lighting conditions while reducing energy consumption in residential environments, thus contributing to the discourse on sustainable architecture and smart energy management.

2 Methodology

This study takes a multi-faceted method to build and analyze the energy systems of a villa, addressing concerns of inadequate illumination and excessive electricity consumption. We deploy sophisticated software tools, including AutoCAD, Dialux Evo, PVsyst, and T*sol, to generate detailed models and simulations. AutoCAD assists architectural design, while PVsyst and T*sol offer full analysis of the photovoltaic and solar water heating systems, respectively. Dialux Evo is applied for precise indoor lighting simulations, and we examine the usefulness of motion detectors in optimizing energy use. Additionally, we add solar lamps for outside lighting, supporting sustainability and cost-effectiveness. This comprehensive methodology aims to boost overall energy efficiency while enhancing lighting quality in the villa. The villa building model evaluated is located in Morocco, precisely in the town of Errachidia, with a longitude and latitude of -4.43° and 31.93°. The initial stage in lighting design is to draw up a simple 2D plan of the villa using AutoCad, as illustrated in Figure 1. This strategy streamlines the job of 3D design on DIALux evo. When DIALux evo opens up, the software's home page offers an Import tab for working on a project needing 3D modeling on an existing 2D plan. This grants access to 100% of the design support tools. The CAD file for the ground floor of the villa is imported into DIALux evo, followed by the first floor. Next, a 3D model of the building is built using DIALux evo software, detailing the type of workstation in each area. DIALux Evo 12.1 uses an extensive library for objects and materials, providing sophisticated, standards-compliant 3D lighting simulation. Figure 2 displays the final 3D view of the villa. In the next step, this model was then simulated, and the photometric parameters are recorded and compared with the requirements of European standards. The annual lighting energy required for the villa was examined in addition to the photometric study to ensure energy management.

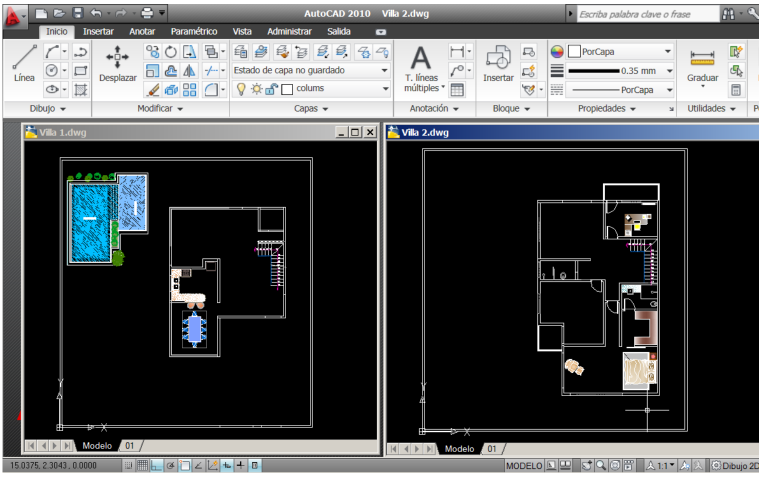


Fig. 1. 2D plan of the villa.

Fig. 2. Construction of the building and insertion of objects, openings, and materials with DIALux evo 12.1.

3 Results and discussion

3.1 Lighting design for the villa

In order to carry out the lighting design, we need to establish solutions that fulfill needs and provide efficient working circumstances by selecting an ideal choice of lamps and their positioning. The DIALux evo program, produced by DIAL GmbH and in existence since 1989, is a powerful tool used to simulate illumination inside and outside rooms, calculate, and check all the parameters of lighting installations in a professional manner, producing precise results in conformity with the newest requirements. This computation is based on standard EN 12462-1. Its functionalities enhance decision-making and efficiency in lighting design procedures. The tool incorporates elements that enhance visual comfort while conserving energy, adjusting to diverse user requirements and furniture arrangements. It facilitates the integration of intelligent technology, including sensors and automation, to boost energy efficiency and user experience [16]. Its capacity to model both artificial and natural lighting conditions facilitates the development of balanced and effective lighting solutions for residential environments.

3.1.1 Artificial light design

In this part, we took care to respect the required lighting settings for each room in the villa to ensure visual comfort and energy optimization. Once the luminaires had been placed, the villa's rooms were illuminated. From Figures 3 to 5, it's evident that the indoor lighting fulfills European requirements because DIALux delivers green boxes instead of red ones (Figure 3), which signifies that the lighting design is nicely done. It's also evident that there's homogeneity throughout the ground level and the first story, as there are no sudden variations in colour (Figure 5). Figure 6 illustrates the decorative lighting in the garden. We have maintained a minimum illumination level of 5 lux utilizing solar lamps, as tiny amounts of light are acceptable for gardening; 5 lux minimum.

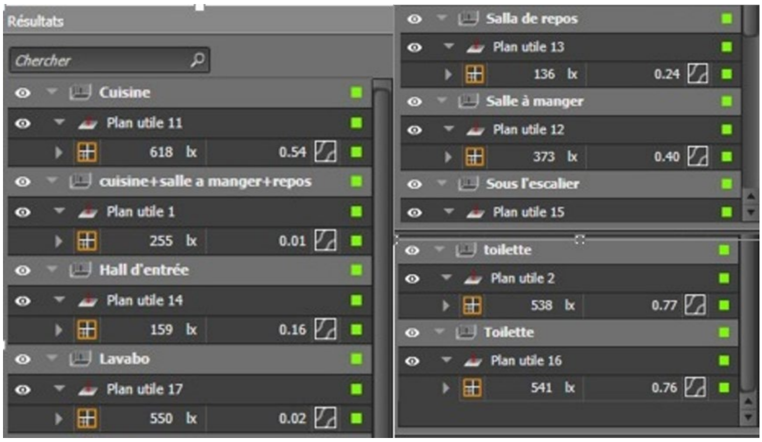
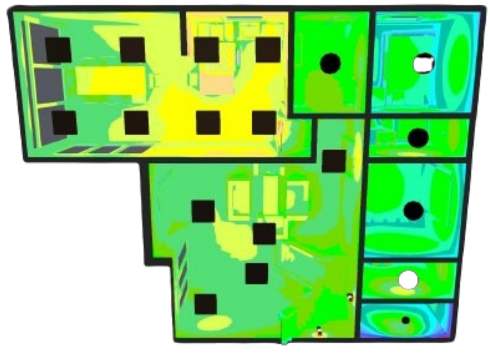


Fig. 3. Lighting levels in the rooms of the villa.

a)

b)

Fig. 4. (a) Illuminated ground floor, (b) Illuminated first floor.



a)

b)

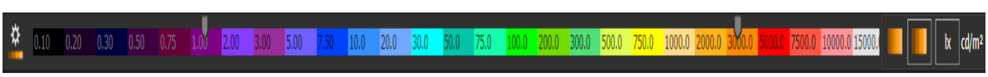


Fig. 5. (a) False colour illuminated ground floor, (b) False colour illuminated first floor.

a)

b)

Fig. 6. The villa's outdoor lighting design (a) & (b).

3.1.2 Smart LEDs lighting design in DIALux evo

In this section, the usefulness of motion detectors in regulating interior lighting to reduce energy usage is studied. In order to reduce the energy spent and the money paid, we propose to make our lighting intelligent, while introducing sensors (available in DIALux evo 12.1) from our network. We place sensors in the villa's rooms so that they scan all the surfaces of the villa as illustrated in Figure 7. The installed sensors work automatically. In other words, they compensate for sunshine when necessary but also activate when there is someone in their field.

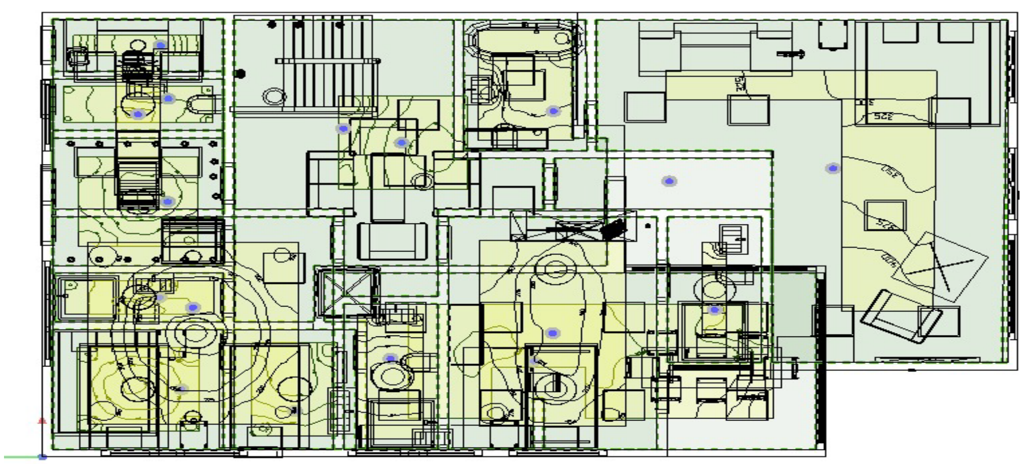


Fig. 7. Inserting the sensors in the villa.

Table 1 provides the energy utilization and cost of the villa before the deployment of sensors. While the integration of motion detectors in lighting simulations offers numerous benefits, Table 2 illustrates the quantity of energy utilized in the villa and its cost after utilizing sensors. In fact, using sensors, the lighting is there when it is needed at sufficient levels. As a result, the energy consumed and its cost are lowered once the sensors have been placed. The sensors have enabled us to lower energy use by 30%. This shows the usefulness of intelligent lighting systems in boosting energy efficiency while maintaining a high degree of comfort and compliance with regulations in green residential environments [17].

Table 1. Energy consumption and costs before using sensors.

Maximum energy demand (kWh/a)	3305
LENI (kWh/a/m2**)**	12 – 14
Costs (€/a)	816 – 991
$\mathbf{CO_2}$ (kg/a)	1090 – 1325

Table 2. Energy consumed and cost after using sensors.

Consumption (kWh/a**)**	2343
Maximum energy savings (kWh/a)	962
LENI (kWh/a/m2**)**	157
Costs (€/a)	702.76
$\mathbf{CO_2}$ (kg/a)	939

3.2 Sizing and design of the photovoltaic system

Solar systems are made up of three major components: solar modules, a battery, and a charge controller. The battery is charged during the day to store energy and can receive a charge current and discharge a discharge current as required. Appliances are connected to the battery via the regulator for optimum charging, and the regulator cuts off the charge when the battery is full. Solar panels deliver DC electricity to the gadgets during the day and charge the battery. A charge controller prevents the battery from being overcharged if too much solar energy is produced. The battery powers the appliances at night or in bad weather, safeguarded by a discharge limiter. An inverter converts direct current into AC current for power equipment requiring this sort of current. The sizing of the standalone photovoltaic (PV) system for the villa was accomplished using a thorough strategy that examined the villa's energy usage patterns, solar irradiance data, and system efficiency using PVSyst software [18, 19]. The yearly energy demand of the villa was calculated to be around 17.817 kWh, based on extensive analysis of equipment (Table 3), usage patterns, and lighting energy consumption determined earlier with DIALux evo software. The average solar irradiation in the region was calculated to be 5.76 kWh/m2/day, which informed the selection of optimal PV panel parameters. A total of 24 panels, each rated at 200 W, were found sufficient to cover the energy needs, producing a total system capacity of 4.8 kW. The system's design also incorporates a battery storage solution with a capacity of 372 Ah to ensure energy availability during periods of low sunshine, hence boosting the system's reliability. The overall efficiency of the system, accounting for losses due to shading and temperature, was estimated at 85%, resulting in a net energy generation of roughly 6.503 kWh yearly. This solution not only meets the villa's energy requirements but also adds to sustainability goals by lowering dependency on fossil fuels. Figure 8 illustrates the electrical plan of the photovoltaic system made up using AutoCAD software. AutoCAD is a computer-aided design (CAD) tool released in December 1982 by Autodesk. Figure 9 illustrates the insertion of PV panels on the top of the villa.

Table 3. The electricity requirements of the villa.

Electric appliances	Quantity	Power (W)	Operating time (h)	daily consumption (Wh)
TV/PC	6	60	3	1080
Fridge	1	100	24	2400
Washing machine	1	200	2	400
Air conditioning	2	500	6	6000
Electric oven	1	700	3	2100
Household appliances	3	150	3	1350
Standby consumption	-	-	24	24

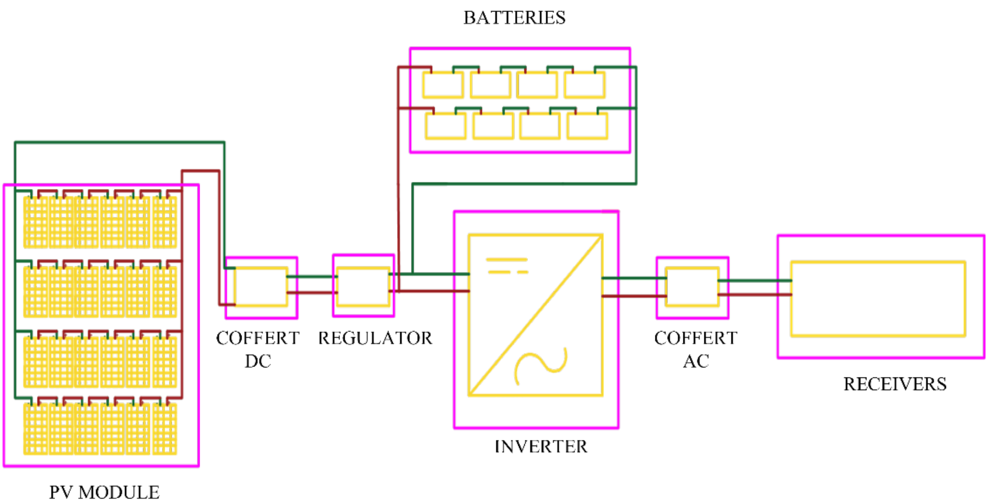


Fig. 8. Electrical plan of the photovoltaic system.

Fig. 9. PV panels on the roof of the villa.

3.3 Sizing and design of solar water heater

Solar water heating (SWH) is suggested as an effective method to mitigate energy consumption, especially for water heating, which represents a substantial fraction of residential energy usage [20]. Various software programs exist for implementing solar water heating systems, including F-Chart, T*SOL, and Polysun, each having distinct features for optimization and simulation. These tools enable for economic analysis, modification of components, and integration of local meteorological data to boost design correctness [21]. In this paper the size and design of the solar water heater for the villa were undertaken using T*sol software, which gave extensive simulations of solar radiation, system performance, and energy requirements [22]. T*SOL PRO 5.5 is a professional simulation software created to optimize solar thermal systems and make energy efficiency evaluations and system design easier. The program computes energy flows using hourly weather data, enabling precise yield forecasts and assessments of system performance. It integrates a number of solar system components, including as heating and hot water delivery systems, to expedite the planning and design stages [20]. The study focuses on a family's average daily hot water usage of 200 L at 60°C. Errachidia-specific environmental data, such as annual global irradiance and temperature fluctuations, are used to assess the system's effectiveness. The research found that the ideal collector area was determined to be 4.04 m2 (Figure 10), producing an annual energy output of roughly 3296.69 kWh. The system was designed to meet 84.4% of the villa's hot water demand, with peak performance happening during the winter months. Additionally, the models suggested averted CO_2 emissions of 848.19 Kg, confirming the practicality of the solar water heating system. Overall, the results indicate the efficiency of using T*sol software for building solar thermal systems adapted to unique home needs. Figure 11 displays the installation of solar water heaters on the roof of the villa made up using DIALux evo software.

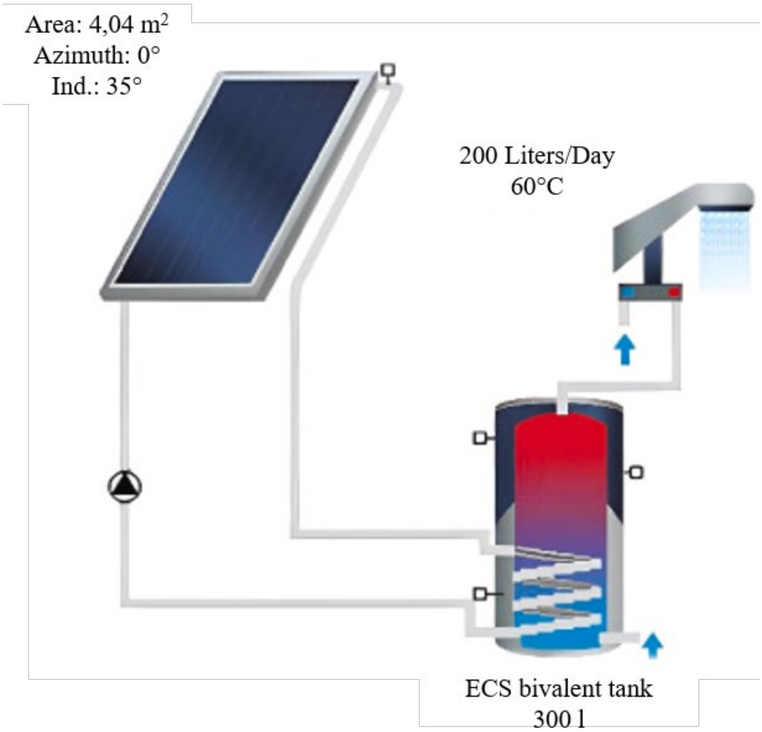


Fig. 10. Sizing of solar water heater with T*sol software.

Fig. 11. Solar water heaters on the roof of the villa.

4 Conclusion

The integration of renewable energy and digital technologies in residential structures presents a huge opportunity to increase energy efficiency, reduce carbon footprints, and promote sustainability. Energy management software, play a crucial role in optimizing energy use and developing sustainable practices among homes. Our work has successfully addressed the major challenges of inadequate illumination and excessive electricity usage in a villa's energy systems. By applying powerful software tools such as AutoCAD, PVsyst, Dialux Evo, and T*sol, we have established a comprehensive design and analysis framework that optimizes both interior and external lighting while incorporating renewable energy solutions. Integrating motion detectors into lighting simulations using DIALux evo boosts energy efficiency and user experience. This connection enables for dynamic lighting management based on occupancy, maximizing both functionality and aesthetics. The introduction of solar lighting indicates a sustainable approach to energy management, considerably boosting efficiency. Ultimately, our findings add to a holistic understanding of energy system design, offering practical strategies for achieving sustainability in residential settings. Future research directions include researching integration with other renewable sources and enhanced monitoring systems that will improve the efficiency and sustainability of solar water heating systems and Building-Integrated Photovoltaics systems. The combination of artificial intelligence (AI) and machine learning boosts these systems' ability to adapt energy savings to individual needs.

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