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Solar PV integration for enhancing energy efficiency of industrial air compressor systems in the unstable environment of Yemen

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ABSTRACT

This study explored the integration of a 7 MW PV solar energy system into the energy system of industrial air compressors to mitigate extensive energy costs in the unstable grid electricity in Taiz Al-Huban, Yemen. A combined approach involving solar PV generation, leakage recovery, and compressor operation control was implemented into Five major food-based companies to enhance system efficiency. Cumulative energy-related data was collected from the proposed companies for several years and then analyzed using PVsyst simulations. Interesting results indicated an energy saving of 20% from repairing of 851 leaking points, with a total energy saving of 1.93 GWh. Simulation results show that the proposed PV system produces 13.8 GWh annually, meeting the compressors' total demand of 9.7 GWh and generating a 4.1 GWh surplus. The system achieved a performance ratio of 81 %, and the optimal tilt angle was identified as 17.5 degrees. Economic analysis confirms strong feasibility with a 2.3-year payback period under the Yemeni electricity price and significant long-term revenue. Environmentally, the system offsets approximately 229,538 tons of CO_2 over 30 years. Overall, the results demonstrate that integrating solar PV with targeted compressor improvements offers a cost-effective and sustainable solution for industrial energy management in developing regions.

Keywords: Energy conservation, Air Compressors, Renewable Energy, Carbon Emissions, Economical Feasibility.

1. Introduction

Air compressors (ACs) constitute some of the largest users of energy in the industrial processes, consuming a good percentage of the electrical energy in the different sectors. In industrialized countries, compressed air systems consume approximately 20% of the total electrical power generated, highlighting their critical role in energy consumption and the potential for efficiency improvements [1]. In certain industries, such as automotive metalworking, compressed air systems can represent up to 20% of a company's total electricity consumption, emphasizing the direct relationship between air demand and energy use [2]. Similarly, in Europe, compressed air systems contribute to approximately 10% of industrial electrical energy consumption; however, their energy efficiency is often overlooked due to inadequate monitoring and control measures [3] . Case studies in pharmaceutical packaging and marine equipment manufacturing demonstrate the significant potential for energy savings through targeted interventions. For example, optimizing compressor performance and minimizing air leaks can reduce electricity usage by 23% [4], while addressing short-cycling issues in compressors can lead to a 73% reduction in energy consumption, resulting in substantial cost savings and lower carbon emissions [5].

These findings underscore the importance of implementing energy-efficient practices and technologies in compressed air systems to enhance sustainability and reduce operational expenses in industrial settings.

Air compressor systems in industries are the utilities that consume the greatest amount of energy in manufacturing premises but are often run with considerable inefficiency including leakage of air, ineffective control measures, and over-sizing of equipment. Mostly, these inefficiencies incur increased operating costs in areas where there is a stable supply of electricity. In Yemen, the electricity infrastructure has experienced significant degradation owing to a prolonged period of political instability instigated by the persistent civil conflict, where the supply of public grid electricity is massively non-existent and most industries are forced to run on diesel generated power at catastrophically high prices, while the expenditure associated with a unit of electricity is approximately four times higher than the global average [6]. Inefficient compressed air systems are of paramount importance to maintain the continuity of production, economic and environmental sustainability. Although the country has a high potential on solar energy the industrial energy sources in Yemen are highly reliant on fossil fuels with little incorporation of renewable energy sources into the core industrial processes including compressed air generation.

The current literature is abundant in terms of energy efficiency enhancement of compressed air systems and the use of solar photovoltaic (PV) systems in industrial environments. Nevertheless, in the majority of the published works, these two domains are considered separately. Most PV research papers typically consider a fixed industrial load and fail to take into consideration any demand side inefficiencies like air leakage and optimal compressor control. On the other hand, the efficiency of compressed air studies seldom considers the effects of demand side enhancement on the optimal sizing, performance, and economics of large-scale PV systems. Also, no empirical studies, which use data to combine large-scale PV generation with measured compressor performance and leakage data in industrial zones in conflict-affected or weak-grid areas like Yemen exist. This disparity restricts the applicability of the current research to areas with severe energy insecurity and electricity prices.

In order to fill these gaps, this research paper contributes to the body of knowledge in the following ways:

1) Conducts an extensive on-site evaluation of five large industrial compressed air systems in Taiz Al-Huban, Yemen comprising of energy audit and ultrasonic leakage identification of leakage points.
2) Measures the effect of preventive maintenance and leakage reduction on compressor energy consumption.
3) Designs and models of a 7 MW solar PV system from PVsyst and explicit sizes the PVsyst based on optimized compressor demand, and not on an uncorrected load base.
4) Assesses the technical, economic, and environmental results of the integrated PV compressor system under local Yemeni conditions including excess-energy, payback time and long-term CO_2 emission savings.
5) Offers a realistic and feasible model of implementing renewable energy in conjunction with industrial utilities in areas with unpredictable grids, high energy expenses and low technical standards.

1.1. Compressed air systems in industrial applications

The industrial processes that utilize compressed air are mostly used to operate tools, make packaging, clean, move, and control. It is an extremely expensive type of energy in most factories where it is a so-called free utility, as vast quantities of electrical power are consumed in compression of air to normal operating pressures. Research on industrial compressed air states that compressed air may consume 10-30 % of the total power consumption of a plant, and in certain industries the percentage may be even greater [7, 8].Compressors make use of mechanical elements to scale electrical input into flow and pressure, which are usually oversized or inefficiently matched to the actual demand profile, which adds to the losses and noise further. Most plants do not know the actual cost of compressed air, and thus their operators just leave the air leakage, improper applications like open blowing, and improperly used to cool or clean without correcting the situation trapping the unwarranted energy usage and unwarranted cost.

Even in cases where the demand profile is highly variable, air compressors are often run at constant speed. This supply and demand mismatch results in part-load operation, high frequency start-stop cycles and unneeded pressure margins all of which raise specific energy consumption [9]. In can production, e.g., compressed air systems were said to consume 38 % of the electricity within the site, which highlights the significance of such systems to the overall energy performance [8]. The same has been observed in food, plastics and packaging sectors where compressed air is not a service, but it is a production input.

Compressors with low part load or no load can be detected during field audits as times when the compressor was not loaded or the compressor was loaded with low part load just to keep the unnecessary high line pressures or to serve intermittent end uses. Not only do such operating patterns increase electricity bills, but also obscure underlying design issues, including over-sized compressors, unsatisfactorily sectioned distribution networks and the absence of storage receivers near key processes, which engineers can correct through specific engineering interventions.

The given observations are directly applicable to the Yemeni case, in which 33 industrial screw compressors are used to feed production processes in five and large companies and make a significant portion of their overall electricity demand. Any form of inefficiency in such a significant end-use will mean a disproportionate economic effect in an environment of unreliable grid supply and high energy costs. The critical analysis of the literature thus proves that compressed air is a proper area of focus when interventions are to be made to increase energy efficiency and when it is connected to renewable energy supply.

In Yemen, where most factories do not use a regular public power supply, but function on diesel generators, the marginal cost of every kilowatt-hour is many times that of countries where utility tariffs are present. Consequently, one kilowatt of compressor load which can be eliminated by improved design, controller or supply-side combination has a direct impact on competitiveness, freeing up limited financial resources to maintenance, raw materials, and strategic investment in production capacity.

Recently, studies of recent times are increasingly considering compressed air as a component of an overall energy system and its demand profile can be re-shaped to match on-site generation by PV or other renewable sources. This systems approach is especially useful with regards to Yemen since it offers solutions to the problem that all work towards optimization of compressors, networks and power supply instead of looking at each component separately.

Recent case studies in international practice are starting to define compressed air not as a discrete utility but as a component of an energy system, with its demand profile re-definable to match on-site generation as based on PV (or other renewable) generation. The systems view is especially useful in the case of Yemen as it indicates towards solutions that jointly optimum compressors, networks and power supply as compared to looking at each individual aspect independently and regulating the stakeholders.

1.2. Energy inefficiencies and leakage in compressed air systems

The literature also demonstrates that compressed air systems are extremely inefficient with 10-30 % of the electrical input being converted into useful mechanical work at the point of use [7]. The rest is massively wasted in form of heat; pressure drops and leakages during the distribution chain. Air leakage is considered to be one of the prevailing preventable losses. Leakages of 20-30% of the total compressed air generation are usual, and in ill-maintained systems the ratio may go to 50 % [10, 4].

In thermodynamic perspective, compression is an inherently lossy process, majority of the energy input is turned into heat which is normally expelled to the environment or rather unnecessary than being retrieved. The combination of this inherent inefficiency with leaks and ineffective control of pressures makes the effective cost of every unit of useful pneumatic work very high and compressed air is one of the least efficient and most carbon-intensive utilities in most factories.

Leakage does not only waste energy but also causes compressors to work at greater loads and longer periods and this accelerates wear and increases the maintenance needs. Various research works indicate that systematic leakage detection and repair schemes are capable of providing energy savings of up to 60% of the leakage losses particularly with pressure optimization and demand-side interventions [7]. An example can be given in the pharmaceutical packaging industry where a joint leak repair and system optimization programme resulted in a 23% cut in electricity usage by compressors, and a 7-8% cut in compressed air usage [4].

Due to these powerful business drivers, leak management is sometimes referred to as a low hanging fruit of industrial efficiency programmes. Investments required in ultrasonic detectors, employee training and a few basic tools to repair leaks are minor in relation to the savings on the electricity bill that would recur repeatedly and in many case studies, simple payback can be achieved in less than a year with leak-repair campaigns combined with operator education, improved housekeeping habits and clear accountability policies.

The leaks are frequently scattered over fittings, joints, hoses as well as mis kept end-used equipment and therefore hard to detect unless specialized equipment is used. The savings that come because of one-off campaigns may be corroded overtime by the introduction of new leaks without monitoring. This highlights the importance of regular check-up surveys and the existence of straight forward performance measures like night-time pressure decay tests to monitor how leakage changes with time.

More sophisticated facilities are also monitored with flow, pressure and power being consumed to draw key performance indicators, including specific energy use per cubic meter of air being delivered. The monitoring of these indicators over time enables maintenance crews to see the slow reappearance of leakage or control issues early before they are apparent in the production process and be able to action data-driven solutions rather than reactive measures to reports of low pressure or increasing energy costs.

These findings endorse the methodology used in the Yemeni study in which ultrasonic detection was used to identify 851 points of leakage and measure their contribution to the compressor energy demand. The study effectively quantifies the number of leaks and the rate of flow they carry out by doing so in an explicit way, thus not relying on a simple estimation to determine the energy and cost-saving of repair. Such detail is yet quite uncommon in literature, particularly in the industrial zones of developing countries.

This systematized quantification also plays a role in the Yemeni case to persuade decision-makers who might be skeptical about such an investment to maintain as being a technical requirement that leak repair is not a mere action of technical nicety but a cost-based act. The study would produce a clear list of opportunities that could be prioritized, budgeted on and monitored over time as part of an ongoing efficiency improvement further by connecting every one of the identified leaks to an annual energy and cost penalty.

1.3. Technologies for enhancing compressor efficiency

Three key paths are usually taken to improve compressor efficiency: the better management of the compressor operation, system losses, and the implementation of the structured energy management practices. Generally, one of the most mentioned technologies in regulating the speed of compressors in accordance with the actual air demand is Variable Frequency Drives (VFDs). VFDs can save 15-35 % of compressor energy by throttling less, avoiding excess unload operation because of varying motor speed, and reducing the throttling loss to zero when throttled perfectly, a benefit of VFDs in appropriate applications [9].

Programmable Logic Controllers (PLCs) and inbuilt compressor control systems are also employed in the coordination of multiple units, maintenance of optimal pressure bands and prevention of inefficient overlap between base-load and trim compressors [11, 12]. Central controllers in multi-compressor stations are especially useful in being able to sequence machines according to efficiency maps and maintenance needs. Nevertheless, some case studies indicate that advanced controllers fail to save when the root cause problems of the system, including leakages and improper applications of compressed air, are not resolved.

Energy Management Systems (EnMS) provide an organizational layer through determination of responsibilities, targets and continued improvement procedures[8]. Effective EnMS implementations usually involve a combination of technical and training initiatives and operator involvement where compressors are turned off when idle, pressure setpoints reviewed periodically and maintenance scheduled rather than response based. Literature therefore indicates that most effective outcomes are achieved when there are combined packages of measures rather than individual technical remedies.

The Yemeni work also represents this combined vision through a combination of leakage repair, preventive maintenance, and operation optimization with the design of the PV supply. It does not presuppose a fixed compressor demand, but rather initially, it lowers the base by low-cost efficiency measures, then it analyses the performance of the new system under the power of solar energy. This sequencing is a good practice standard of industrial energy management but is not currently widespread in the published case studies.

1.4. Solar photovoltaic (PV) systems for industrial use

Solar photovoltaic (PV) systems present a viable solution for industrial energy needs, offering significant economic and environmental benefits. Research indicates that these systems can substantially reduce energy costs and greenhouse gas emissions across various industrial applications. For instance, a study at SULFO Industry demonstrated a payback period of approximately 10 years, with annual energy generation of 502.2 MWh, leading to a reduction of 6,555.1 tons of CO2 emissions [13]. Similarly, a 910 kW PV system in Turkey is projected to cover 20% of an industrial facility's electricity needs, achieving annual savings of $318,376.66 and a payback period of just 2.7 years [14]. In Egypt, different PV configurations showed feasibility with significant energy production and CO2 reductions, emphasizing the adaptability of solar technology to local conditions [15]. Furthermore, economic analyses in Italy highlight the importance of self-consumption in enhancing the financial viability of PV investments in non-subsidized markets [16].

The integration of solar collectors with compressed air systems can enhance thermodynamic performance, reduce carbon emissions, and increase net present value of the net, making them attractive from both economic and environmental perspectives [17]. moreover, the integration of solar energy systems with ACs not only supports energy sustainability but also offers economic and environmental benefits, making it a viable solution for industrial applications [18]. Overall, while barriers such as high initial costs and limited awareness exist, the integration of PV systems in industrial settings is increasingly recognized as a strategic move towards sustainability and cost efficiency [19].

Most of the industrial PV research studies consider the PV plant as a single-purpose generator, and it is not employed to assess how its output compares with particular final use like compressed air. PV generation against process demand is more often compared by time and more often reported, and in most instances a generic payback computation is conducted. The current research is a continuation of this research with the explicit identification of PV production against compressor demand patterns, as well as quantification of excess energy, which could be exported or utilized in other loads.

1.5. Hybrid and PV/T systems for performance enhancement

Hybrid photovoltaic-thermal (PV/T) systems significantly enhance energy conversion efficiency by integrating both electrical and thermal energy generation. These systems utilize innovative designs, such as dual-channel configurations that separate solar spectra for optimal absorption, and advanced cooling techniques using nanofluids to mitigate overheating, thereby improving performance by up to 44% compared to standard PV modules [20]. The incorporation of thermoelectric components in hybrid systems, like the photovoltaic-thermal-thermoelectric (PVT-TE) model, further boosts efficiency, achieving increases in output power by 32.59% to 55.93% over conventional systems [21]. Additionally, new heat exchanger designs have shown improvements in open circuit voltage and overall power output, demonstrating the potential of PV/T systems to leverage excess heat for enhanced performance[22, 23]. Overall, these advancements indicate a promising direction for sustainable energy generation through hybrid systems.

Generally, the literature on hybrids and PV/T exhibits high technical potential, although it provides insight into the difficulties of complexity, reliability, and scalability. Numerous of the reported systems are still pilots or prototypes, and there is little information on the long-term performance of real factories. A simpler fixed-tilt PV system might be more suitable in the short run in the context of Yemen where the technical capacity and supply chains are limited. The current study suggested a (PV/T) system for keeping the temperature of PV panels between 30-35 degree in optimum situation to produce energy. The existing research thus concentrates on the traditional PV technology when it is mentioned that further developments may involve improved cooling or hybrid stores in the future after proper reliability is achieved.

1.6. Integration of PV with compressed air systems

Integrating photovoltaic (PV) systems with compressed air systems in industrial settings offers several significant benefits, primarily enhancing energy efficiency and sustainability. The combination allows for the effective utilization of intermittent solar energy to power air compressors, improving the overall utilization rate of PV-generated electricity. Research experiments with solar-powered air compressors and PV-driven electric compressors indicate that a process of aligning PV energy generation with compressor utilization can greatly decrease power usage in the grid or diesel to drive industry air supply [24].Integrating advanced technologies added to PV such as frequency converters and programmable logic controllers (PLCs) in ACs has improved system stability and efficiency, indirectly supporting leak management by maintaining optimal operating conditions [11, 12]. These technological advancements, in conjunction with structured improvement processes and strong collaboration between engineering and management, are vital to achieving sustainable energy efficiency in industrial settings.

However, these studies are mostly based on prototype-size systems, small workshops or stand-alone rural use and the studies do not pay much attention to large industrial clusters. Also, most fail to consider the internal inefficiencies of the compressed air systems themselves, assuming the compressor demand profile to be fixed. Consequently, the savings reported would be less than those that could be realized considering the leakages and control challenges were resolved in parallel.

The current study is different in two aspects. First, it is founded on actual compressor information of five large industrial corporations in Yemen, which contains specifications of both leakage and load profiles. Second, it combines PV integration and the specific efficiency measures including leak repair, preventive maintenance and smart control. This integrated solution enables the PV system to be scaled and optimally compared to a useful, not wasteful, compressed air demand. By so doing it offers a more realistic estimation of the technical as well as the economic advantages of solar driven compressed air in an industrial zone.

1.7. Comparative analysis with existing similar studies

Practical standards applicable to the design of the Yemeni 7 MW can be found in a few published projects of equivalent nominal PV power shown in Table 1 that contain a comparison between the current study and other literature in the same field. The PR of the current study (81%) is also in line with the PR of the Libyan hospital project (83%) and Malbaza simulations (79.5%). It means that the design based on PVsyst can be confident in a variety of climates. The PR of Malbaza is 70.8% [27] , which shows that it is necessary to mitigate site-related losses like dust and grid instability. Combining compressors control and maintenance, this project maintained a higher level of efficiency and reduced the difference between the simulation and real performance.

The proposed system generated 13,785 MWh per year, which is 4,095 MWh higher than the demand by the industry. This excess, which amounted to 29.7%, is similar to the Thai case, in which the integration of BESS allowed achieving almost 100% of the demand [28]. The two cases indicate that the use of storage and control strategies is important in stabilizing industrial supply. The current example demonstrates that despite the lack of sophisticated BESS optimization, it is possible to export or redirect the surplus energy and improve financial gains.

The current study applied system-level maintenance by correction of compressor inefficiencies, which decreased the level of energy usage by 20%. This proactive load-side optimization strategy is indicative of more general tendencies in the improvement of PV systems, especially the addition of new energy storage methods and materials. The recent developments of PV materials and system designs, such as hybrid systems, smart energy storage, among others, as noted by Dada and Popoola [28] will play a crucial role in enhancing reliability, intermittency control, and maintain high performance ratios in industrial applications. These developments are consistent with the focus of the Yemeni study on operational efficiency and surplus management of energy, which supports the importance of maintaining and designing systems in long-term PV performance.

Optimization of the tilt angle of 17.5° in Yemen is consistent with predictive modeling research, which focuses on site-based design [29]. According to the Malbaza projects, the losses of temperature and irradiation prevail [27]. The Yemeni study achieved maximum yield at minimum loss by applying optimal tilt and controlling compressor demand, which validated the fact that the design must be adapted to local conditions.

Table 1**.** Comparison with existing literature

Study	Objective	Findings	Merits	Limitations	Current Study
[27]	Design and simulate a 7 MW PV at Bani Walid Hospital, Libya	Annual output ~18.92 GWh, PR 83%	Comprehensive design, PVsyst accuracy, promotes renewable reliance	No economic analysis, and long-term challenges are not detailed	PR 81%, annual output 13,785 MWh, surplus 4,095 MWh, payback 2.3 years, CO_2 savings 229,538 tons
[28]	Review of recent advances in PV materials and systems for energy storage	Highlights progress in PV materials, efficiency improvements, and integration with storage systems	Strong focus on energy storage, scalability, and sustainability	General review lacks plant-specific performance data	Supports the current study emphasis on storage, efficiency, and sustainability; aligns with surplus energy utilization and economic feasibility
[29]	Compare PVsyst predictions with Malbaza 7 MW PV	Predictions aligned but overestimated irradiation, ~70% correlation	Validates PVsyst with site-specific data	One-year data, dust/grid issues not quantified	Tilt optimization validated (17.5°),study in five companies PR 81% aligns with predictive accuracy.
[30]	Evaluate control strategies for 7 MW PV in Thailand with BESS	BESS with energy time shift met 99.98% demand, ~253,523 MWh over 25 years	Strong control strategy comparison, BESS benefits	Case-specific, cost assumptions sensitive	Industrial load met fully, surplus energy 29.7%, 22 MWh storage, economic feasibility confirmed

Study	Objective	Findings	Merits	Limitations	Current Study
[31]	Compare measured vs simulated PR in Malbaza, Niger	Measured PR 70.8%, simulated 79.5%, annual 12,746 MWh	Identifies main loss sources, real-world validation	Limited to one year, no economics	Losses reduced through compressors maintenance for five companies; PR is higher at 81%
[32]	Review of solar PV for sustainable development	Highlights PV's role in CO_2 reduction, energy security, and industrial adoption	Broad sustainability framework (STEEP model), links PV to SDGs	General review, lacks plant-specific data	Confirms industrial PV integration as sustainable, aligns with CO_2 savings, and has a short payback

Although both Thai and Libyan studies are context-specific, the Yemeni case illustrates that the case is applicable in a broader context in developing countries with unstable grids. also reinforces this point of view by placing PV integration in the context of the Sustainable Development Goals (SDGs) and the STEEP model [32]. This ascertains that industrial PV deployment is not merely technically viable but also a route to sustainable development, energy security, and mitigation of climate change.

1.8. Identified research gaps and novelty of this study

The analyzed literature shows a few gaps that the current research fills. To begin with, despite numerous papers quantifying the inefficient nature of compressed air systems and emphasizing the need to focus on leakage minimization, few of them incorporate comprehensive leakage mapping, preventive maintenance, and control optimization among large industrial locations. The study on Yemen is valuable because it uses ultrasonic detection to determine the leakage points at 851 points on five factories and quantifies the energy waste that can be reduced by focusing on the compressor electricity consumption, which is found to be 20%.

Second, the literature on PV integration with industry commonly assumes that the industrial load is constant, and it does not consider the fact that efficiency gains can vary the optimal size of PV and financial performance. This work demonstrates that a combination of measures on both sides of the meter can be coordinated to ensure that the maximum technical and economic benefits can be obtained by explicitly relating demand-side improvements in compressed air systems to the design and evaluation of a 7 MW PV plant, also the gap that has been common in most studies is that of economic feasibility. The projects in Libya and Nigeria lacked the payback analysis [31, 27]. Conversely, the Yemeni one estimated a 2.3-year payback, which is supported by global standards. [32] supports this position, noting the role of PV in sustainable development and reduction of CO_2. The 229,538 tons of CO_2 saved in the Yemeni project is a good example of the environmental benefits outlined in the review, and it makes the project better financially and environmentally in volatile situations.

Third, although some 7 MW PV plants have been reported in Libya, Niger and Thailand, those are generally discussed as either power plants or PV-plus-storage systems with little reference to particular applications of compressed air [27, 30, 31]. The present study, as far as the author knows, is one of the first ones to combine a 7 MW PV system with actual data of industrial compressors in Yemen where the grid is unstable and the electricity prices are incredibly high. The work hence builds on the body of evidence concerning the use of PV in conflict-affected or weak situations where the continuity of industries is of paramount importance.

Lastly, numerous sources on hybrid and PV/T systems typically involve advanced prototypes or small-scale experiments [20, 21, 22, 23]. Conversely, this paper is practical in the engineering approach, based on proven PV technology, optimization of fixed-tilt (17.5°) and realistic performance assumptions to aid the immediate deployment. The current study suggested a (PV/T) system for keeping the temperature of PV panels . Simultaneously, it recognizes that the performance may be improved in the future, though, by adding better cooling of PV or storage, when the principle PV to compressor integration will be demonstrated to be operational.

In conclusion, the novelty of the research is that they combined the efficiency of compressed air, large-scale PV integration, and economic and environmental evaluation, which are based on actual industrial data in Yemen. This combined strategy directly addresses the gaps found in the literature and gives a model that can be used in other similar industrial zones of countries with unreliable grids and high cost of energy.

2. Research method

2.1. Study area and industrial overview

The present study was carried out in one of the biggest industrial regions in the country, the Al-Huban industrial zone of Taiz, in Yemen. The region contains some of the large food, packaging, and plastic industries that have continuous production which depends on compressed air systems. It revolved around five factories that are representative of various industries, which are biscuits, dairy, sponge and plastics, sweets and snacks, and packaging. The targeted companies consider as the largest companies in Yemen that consumed 59756149 kw to produce 837812 ton annually and the compressed air systems occupy approximately 16% of the total demand. In these five industries, twenty-nine screw-type compressors are in place that utilize air. Both compressors have twin interlocking rotors in a sealed casing and have nominal capacities of 630-2040 m³/h. The continuous demand of production in a majority of compressors results in high electricity consumption. These manufacturing facilities have been chosen due to three reasons first, they have terrible grid instability and power blackouts; second, they have high and steady electricity requirements of air-compressors; and third, they have enough rooftop and land areas where a multi-megawatt photovoltaic (PV) installation can be installed. The study area is between 13.63 o N and 44.11 o E. The designated industrial location is distinguished by its potential to optimize the yield from the photovoltaic system, given that Taiz experiences a hot, semi-arid climatic condition, wherein temperature peaks fluctuate between 24-32°C and minima range from 11-20°C, accompanied by an average daily insolation of 11-13 hours[33, 34] thus, it is suitable in the production of solar energy. The solar PV with enhanced compressor efficiency was meant to decrease reliance on fuel, enhance reliability and sustainability of the five industries. The overall research methodology adopted in this study is illustrated in Figure 1.

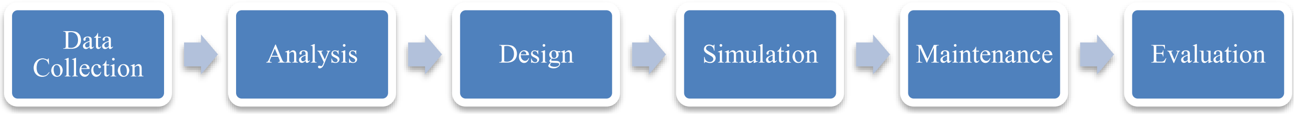


Figure 1. Methodology flowchart

2.2. Data collection

The collection of data was done through a systematic process of both solar and industrial. Two groups of data were obtained: (i) solar resource and meteorological data, and (ii) compressor and leakage system data.

The solar data was retrieved using Meteonorm 8.2 which provided hourly records of the global horizontal irradiance, diffuse and direct radiations, ambient temperature and wind speed of Taiz, Al-Huban [35]. These data were then fed into PVsyst V8.0.6 to model the solar energy access and the PV system performance. The data were employed in computing the annual in-plane irradiance, the optimal tilt angles, and the temperature changes that influence the PV output.

The five companies chosen provided industrial information. Electrical records and sub-meter of factory were examined to establish the gross electrical consumption by air compressors per annum. The value of each compressor in terms of power, pressure, capacity and working hours were noted. Direct power measurement over 7-day cycles per compressor was done with a portable data logger (ALM 20- 3 phase 3 CT Power Quality

Analyzer) to measure these cycles when production was at different times of the year to capture seasonal differences.

An ultrasonic leak detector (UltraCam LD 500/510) was used to detect the air leakage, and it has an ability to detect leakages with high accuracy. Tests were conducted in normal production periods so that the system was pressurized.

The data logging sampling frequency was fixed to one minute, and the duration of the monitoring campaign took 12 months. The data recorded was compressor operating hours, power consumption, pressure variations and production downtimes. These data were used as the basis of system analysis, PV sizing and performance analysis.

2.3. Compressed air system analysis

Analysis of compressed air systems entailed the quantification of compressor energy consumption, and the estimation of leakage losses, and calculation of performance baseline.

The annual energy consumption of each compressor was calculated using following Equation

$$E_{\text{comp,i}} = P_{\text{rated,i}} x t_i x LF_i \tag{3.1}$$

where $P_{\text{rated,i}}$ is the rated motor power (kW), t_i is the annual operating hours (h/year), and LF_i is the measured load factor (ratio of actual to rated power).

The total annual energy consumption of all compressors was then determined as:

$$E_{\text{comp,tot}} = \sum_i E_{\text{comp,i}} \tag{3.2}$$

The results showed a combined compressor electricity demand of approximately 9,690 MWh/year.

The air leakage rate was estimated for each identified leakage using following Equation:

$$q_{\text{leak,j}} = C_d x A_j \sqrt{\frac{2(P_1 - P_2)}{\rho}} \tag{3.3}$$

where C_d is the discharge coefficient (typically 0.65 for orifices), A_j is the effective leak area (m²), P_1 and P_2 are internal and external pressures (Pa), and ρ is air density (kg/m³). The total leakage flow Q_{leak} was obtained by summing individual leaks across all points.

The annual energy wasted due to air leakage was then computed as:

$$E_{\text{leak}} = P_{\text{leak}} x SEC \tag{3.4}$$

where SEC is the compressor's specific energy consumption (kWh/m³). Two efficiency indicators were used for benchmark system performance:

$$f_{\text{comp}} = \frac{E_{\text{comp,tot}}}{E_{plant,tot}} \tag{3.5}$$

$$f_{\text{leak}} = \frac{E_{\text{leak}}}{E_{COMP,TOT}} \tag{3.6}$$

These represent the fraction of total plant energy used for compressed air and the proportion lost to leakages, respectively.

Since $E_{\text{comp,tot}}$ is Total energy consumption of all compressors (kWh), $E_{plant,tot}$ is the Total energy consumption of the entire plant/facility (kWh), $E_{\mathbf{leak}}$ is the Total energy loss due to leaks (kWh) and the $E_{COMP,TOT}$ is Total energy consumed by all compressors (kWh)

2.4. Solar PV system design

The PV system was designed to fully supply the compressor load and generate surplus energy to the internal industrial grid.

The design capacity was determined using following Equation:

$$f_{\text{PV,req}} = \frac{E_{\text{comp,RED}}}{H_{POA} X PR_{tar}} \tag{3.7}$$

where $E_{comp,red}$ is the reduced compressor energy after maintenance (MWh/year), H_{POA} is the annual global irradiation on the tilted plane (kWh/m²), and PR_{tar} is the target performance ratio. Using H_{POA}=2,438 kWh/m²/year and PR_{tar}=0.81, the required capacity was approximately **7 MWp.**

The final design consisted of **9,720 monocrystalline PV modules** rated at 720 W each**, three 2 MW inverters,** and a **battery storage capacity of 24,927 kWh**. The modules were mounted at an optimal fixed tilt of 17.5°, facing due south. The Photovoltaic/Thermal (PV/T) system was incorporated conceptually by adjusting the thermal coefficients in PVsyst to represent module cooling, rather than by modelling full fluid circulation .

The PV cell temperature and corresponding electrical efficiency were computed using Equations (3.8) and (3.9):

$$T_{cell} = T_{amb} + \frac{(NOCT - 20)}{800} xG \tag{3.8}$$

$$\eta_e = \eta_{ref} \left[1 - \gamma(T_{cell} - 25)\right] \tag{3.9}$$

where NOCT is the nominal operating cell temperature (°C), G is irradiance (W/m²), $\boldsymbol{\eta}_{ref}$ is the module reference efficiency, and γ is the temperature coefficient (1/°C). Cooling effects from the PV/T integration were represented as a 3–5°C reduction in T_{cell}, improving electrical conversion efficiency by approximately 1.5–2%.

The battery storage requirement was calculated to ensure uninterrupted compressor operation.

The necessary battery capacity E_{batt} (kWh) for an autonomy period t_{aut} was determined by following Equation:

$$E_{batt} = \frac{P_{load} x t_{aut}}{\eta i_{nv} x DOD} \tag{3.10}$$

where P_{load} is average compressor demand (kW), ηi_{nv} is inverter efficiency, and DOD is the maximum permissible depth of discharge.

2.5. Integrated PV–compressor design strategy

The integrated system combines demand-side management of the compressors with supply-side optimization from the PV system.The design strategy followed six steps:

1. Quantify baseline compressor demand and leakage losses.
2. Apply maintenance and leakage repair to establish a reduced demand profile.
3. Use the optimized demand to size the PV array and battery capacity.
4. Integrate PV, storage, and compressor controls under a single management system.
5. Model thermal effects through PV/T assumptions to assess energy yield improvements.
6. Conduct financial evaluation using standard economic indicators.

The performance ratio (PR) was determined from the PVsyst simulation using following Equation:

$$PR = \frac{E_{AC}}{P_{PV,STC} x \frac{H_{POA}}{G_{ref}}} \tag{3.11}$$

where E_{AC} is the annual AC output, $P_{PV,STC}$ is installed DC capacity, H_{POA} is the measured solar irradiation, and G_{ref}=1,000 W/m².

Economic evaluation was performed using **return on investment (ROI)** equations:

$$ROI = \frac{(Annual\ Revenue - Operational\ Cost)}{Initial\ Investement} \times 100\% \tag{3.12}$$

The design ensured that PV electricity supplied all compressor demand while producing a 29.7% annual surplus that could be exported through the internal grid.

2.6. Simulation setup

The entire system was simulated using PVsyst V8.0.6 to estimate energy yield, identify system losses, and evaluate performance. The simulation incorporated real climatic data and equipment parameters listed in Table 2 of the system.

Table 2. System design information

PV Modules		Inverter	
Manufacturer	Luxor	Manufacturer	Siemens
Model	LX-720-M-210-132-GG-Bifacial	Model	Sinacon PV 2500
Unit Nom. Power (Wp)	720	Unit Nom. Power (kWac)	2000
No. of Modules	9720	No. of Inverters	3
Nominal Power (kWp)	7000	Nominal Power (kWac)	6000
Pnom Ratio (%)	93	Pnom Ratio (%)	93
Orientation	Fixed Panel		
Title /Azimuth	17.5/0°		
Batteries		**Back-up Generator**	
Manufacturer	Huawei	Manufacturer	Caterpillar
Model	Luna2000-4.5 MWh - 2H1	Model	3516H-HD
No. of Units	7 in Parallel	No. of Generators	1
Voltage (V)	1325	Wattage (MW)	1.8
Nominal Capacity (Ah)	23520	Speed (RPM)	1500
Storage Energy (kWh)	24927	Voltage (V)	10500
Pnom. Ratio (%)	95-97	Frequency (Hz)	50
Discharging Under Average Load (h)	22.5		
Discharging Under Maximum Load (h)	17.7		

The key configuration steps included:

- Importing Meteonorm climate data and defining site location.
- Entering the 7 MWp PV array and inverter specifications.
- Setting the optimal tilt (17.5°) and azimuth (0°).
- Configuring battery storage capacity, voltage, charge/discharge efficiency, and state-of-charge limits.
- Defining loss factors for temperature, mismatch, soiling, wiring, inverter, and auxiliary systems.

2.7. Preventive maintenance and optimization

Preventive maintenance strategies were implemented to mitigate energy losses and ensure optimal performance. The key actions included:

1. Regular inspections and scheduled maintenance to prevent recurring leakages.
2. Deployment of advanced ultrasonic sensors to detect and address potential leakage points in real time.
3. Comparative analysis of test results, focusing on reductions in air leakage rates, energy consumption, and cost savings.
4. Operational adjustments based on energy demand fluctuations to prevent overuse and minimize excess power consumption.

The system was fine-tuned to maximize solar energy utilization, reduce compressed air losses, and enhance overall energy efficiency in industrial operations (IO).

2.8. Schematic model of the proposed system

Figure 2 illustrates the proposed model for integrating a Photovoltaic (PV) system with an air compression system to supply energy for industrial applications in Taiz Al-Huban. The schematic model consists of several interconnected components, ensuring an efficient, renewable, and sustainable energy supply for the ACs and IO.

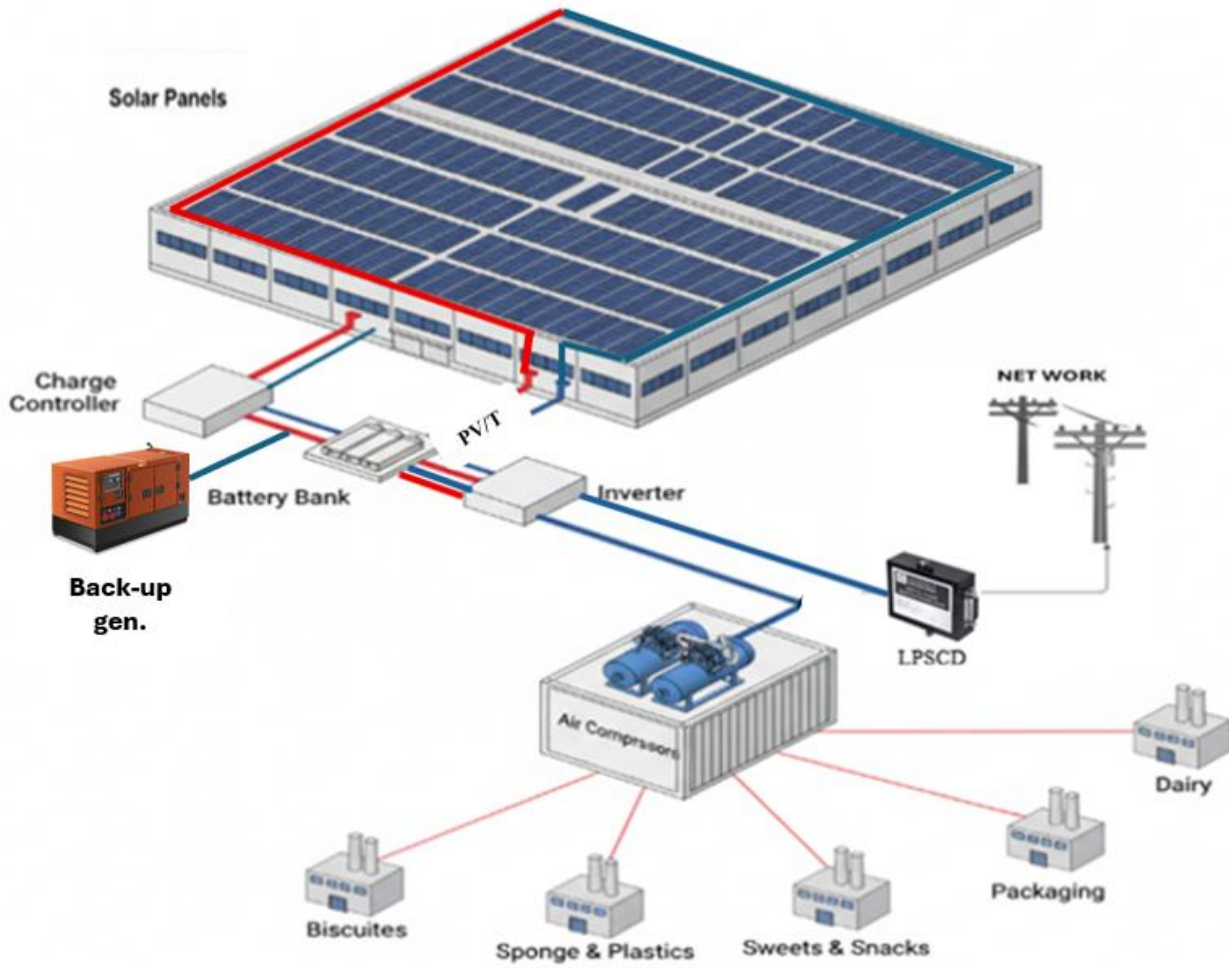


Figure 2. Model of Integrated PV System with Air compressors system in Taiz Al-Huban (Proposed model for this research study)

The system consists of:

1. Photovoltaic (PV) System: This system starts with 7 MWp of solar modules which transform solar radiation into DC power . The array has a thermally optimized PV/T mechanism that ensures that the solar modules are held at temperatures close to ambient conditions and providing high conversion efficiency .
2. Controller: The electricity generated from the PV panels is first regulated by a solar charge controller, which optimizes power flow to the battery storage system and prevents overcharging.
3. Battery System: The 24,927 kWh lithium-ion battery is used to supply energy when the solar energy is not sufficient to feed the compressors up to 20 hours of autonomy.
4. Inverter: DC energy that has been stored or is generated is converted into AC electricity that can be used in industries by inverters. Their overall efficiency is more than 96% high.
5. Air Compressor System: The compressor receives its feed directly on the AC. The central header distributes compressed air to all the factories with the required stability of pressure as well as redundancy.
6. Control System: The control system is responsible for operational adjustments based on energy demand fluctuations to prevent overuse and minimize excess power consumption. This feature allows the ACs to operate efficiently, reducing energy waste and extending system lifespan.
7. Grid/Network Connection: Excess power is optionally exported to the internal industrial network via line-phase shift control device (LPSCD) enhancing the use of energy and the economics of the system.
8. Back-up Generator: This 1.8MW diesel generator provides backup during prolonged low-sun times or during maintenance endeavors that may call upon PV shutdown. The generator is automatically triggered by a control system when the charge in the battery goes below 20% level.

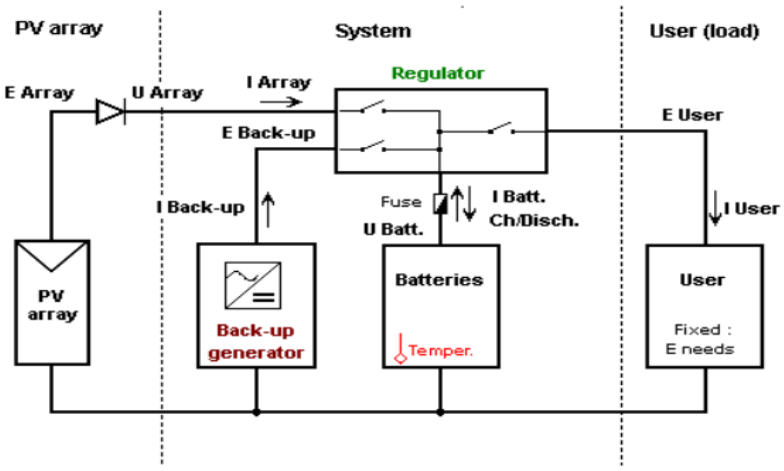


Figure 3. typical sketch for the system

A Figure 3 showing the path of the electrical current to supply the end user (air compressors), where the solar panels are the main source of energy and the backup generator works as a source that guarantees that the power supply to the air compressors will not be interrupted due to the absence of sunlight or the decrease in the energy generated from solar energy, and the regulator works to coordinate between them according to need.

3. Results and discussion

3.1. Baseline energy consumption of industrial air compressors

The initial step in this research was to measure the electricity consumption under the compressed air systems in the five companies of Taiz Al-Huban industries. Table 3 is the summary of the key production and energy indicators of the biscuits, dairy, sponge and plastics, sweets and snacks, and packaging factories, namely, total electricity of the plant, compressor electricity use, and proportion of compressor electricity use in the plant. The five plants are collectively yielding 837,813 tons of products annually and use 59,756 MWh of electricity. The twenty nine screw air compressors use 9690 MWh per year, which represents 16% of the total electricity demand. This proves that compressors are a major cause of energy expenses in the industrial sector.

Table 3. Data related to the energy, capacity and air compressors ‘leakage of companies under study

Company	Biscuits	Dairy	Sponge & Plastics	Sweets & Snacks	Packaging	Total
Production Capacity (Ton/Year)	120000	365000	200813	117000	35000	837813
Annual Energy Consumption in Factory (MWh)	14905	21732	15053	3462	4604	59756
Annual Energy Consumption by Air Compressors (MWh)	2102	3694	2620	670	604	9690
Ratio of Energy Consumption by Compressors (%)	14	17	17	19	13	16
Air Compressors Units	8	5	11	5	4	33
Leaking Points (No.)	319	89	218	146	79	851
Annual Volume leaking m³	6817541	2631556	4350492	2890160	2214708	18904457
Annual Energy Loses (MWh)	818	316	522	347	266	2269
Ratio Of Energy Loss to Air Compressors Energy Consumption (%)	39	9	20	52	44	23
Energy Cost ($0.4/kWh)	327200	126400	208800	138800	106400	$907600

This analysis at the company level indicates that compressors take 13 to 19 % of the annual energy consumption in each factory, with the sweets and snacks plant and packaging factory recording the highest and lowest, respectively. These values have been shown to be close to the literature values of energy intensive manufacturing industries where compressed air usually constitutes 10-30 % of power usage[7, 8]. The systems have operating hours of approximately 8,760 h/year, as majority of compressors are operating virtually round-the-clock to sustain the pressure in various production lines. High utilization increases the effect of any inefficiencies, since any kilowatts of possible compressor load is multiplied by a long annual operating period.

Figure 4 shows the Annual energy consumption and compressor losses per company. The bar chart also brings out the fact that the dairy and the sponge and plastics factories are the largest consumers of electricity, and also have the highest absolute compressor consumption, more over the Sweets & Snacks and packaging factories have the highest percentage of loses among factories, since the total energy loses found 2269 (MWh), which represent by 23% of the total energy consumption of air compressors, in terms of industrial operations, these outcomes are worth directing efficiency initiatives at the compressed air systems, savings in percentages correspond to huge absolute energy and cost savings.

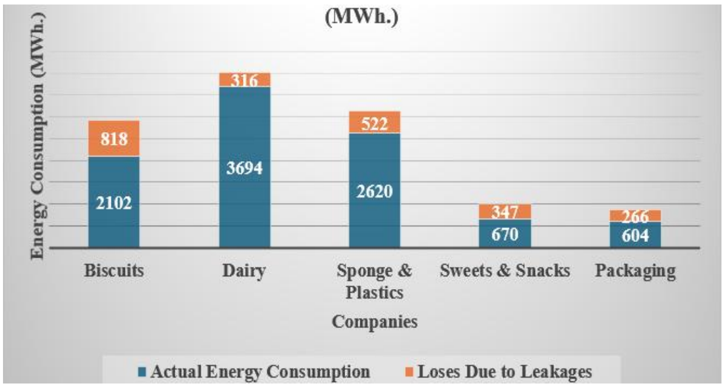


Figure 4. Annual energy consumption and losses of the companies air compressors

3.2. Air leakage assessment and loss quantification

The ultrasonic survey leak survey revealed that there were 851 leakage points in the five factories. These leaks were spread all over the compressed air networks inclusive of joints, valves, hoses and final use equipment. The total leakage of compressed air was determined as 18,904,457 m³ using the ultrasonic readings and the calibrations of the orifice correlations. When this is added to the specific energy consumption of the compressors at the operating pressure, the resultant electrical loss comes to 2269 MWh/year which is given in Table 3. This implies that approximately 23 % of electricity saved by compressors is wasted just to feed leakages, which is within 20-30 % or over that of leakages commonly quoted in industrial reviews [4, 7].

Financially, the leakage losses occupy around 907,600 USD annually in case the electricity is priced at 0.40 USD/kWh. The largest share of such wasted energy is dairy and sponge factories since both use multiple large compressors and have complex piping networks. A large number of leaks are produced with respect to relatively insignificant fittings or connections, but when added up the number amounts to a significant sum when multiplied with 8,760 working hours. These findings indicate that leakage reduction is not a peripheral indicator but a fundamental part of any energy efficiency initiative in compressed air systems. The amount of leakage discharged, and the loss of energy is what is quantified and forms the foundation of the preventive maintenance programme mentioned above. They also offer a necessary factor in the economic analysis, as the annual leakage costs are a sort of virtual fuel bill, which can be minimized by spending comparatively less capital.

3.3. PV system simulation results

PVsyst was used to simulate the PV system with the Meteonorm climatic file of Taiz Al-Huban[35]. One of the main design considerations was to optimize the tilt angle of the modules so as to maximize yearly energy output. Figure 5 shows the modeled yearly energy generation and international irradiation on the collector plane at a number of tilt angles of 0 to 35 degrees. The energy output given at 0° tilt is 13,323 MWh annually. With the increase in tilt, the production of energy increases to maximum of 13785 MWh at 17.5°. After this, the yield decreases and becomes 13, 263 MWh at 35, thus the optimum tilt is 17.5° alien with Hashed et. al study result [6]. Some studies which conducted in Konya, Turkey, where optimal tilt adjustments resulted in a 6.19% improvement in energy production. However, excessive tilt angles led to reduced efficiency [36]. The optimization of tilt angles is a crucial factor in maximizing the performance of solar PV systems [37, 38].

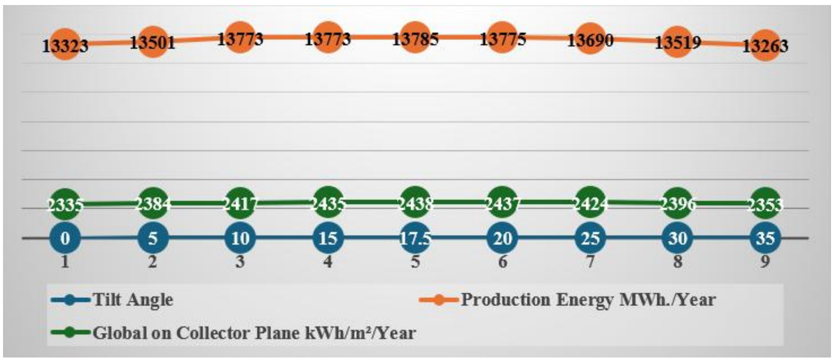


Figure 5. Tilt angle orientation with production energy output and global on collector plane

This is in agreement with earlier optimum optimization studies at the same latitude that indicate small though significant savings when the tilt is optimized to the local solar configuration. The difference between the optimum and a horizontal array in this case is approximately 3.5% or more than 460 MWh/year. In the case of an industrial plant with high electricity prices, this additional generation is simply reflected in extra savings.

Table 4 contains the main PV system parameters. The last set up is monocrystalline modules of 7 MW with fixed tilt 17.5° with three central inverters that supply the industrial AC bus. The annual energy production simulated is 13,785 MWh which is an average of 38 MWh/day. Top instantaneous AC power is approximately 6 MW, in comparison to the top compressor demand, but less than the installed DC capacity as it should be owing to derating and losses. Simulation also reveals that approximately 18.32 MWh/day can be charged to batteries and mean amount of excess energy which remains after satisfying compressor load and battery charging demand is 11.22 MWh/day.

Table 4. System parameters

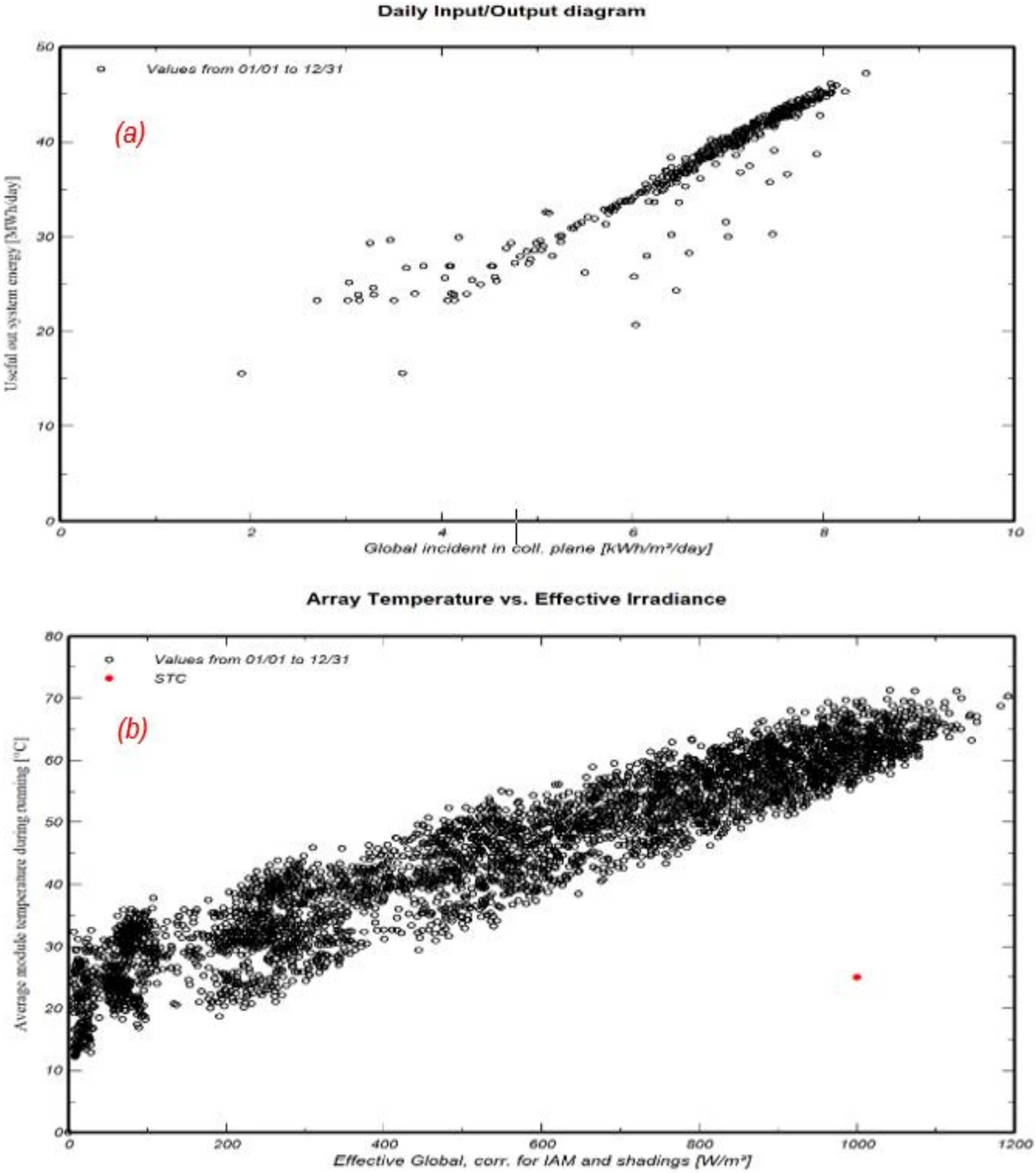
System characteristic	Value
PV System Size	7 MW
Meteorological Data Source:	Meteonorm.
Tilt Angle	17.5°
Global on Collector Plane (kWh/m²)	2438
Transportation Factor FT	1.04
Loss with Respect to Optimum	0.0%
Air Compressors Energy Consumption (MW/Year)	9690
Average Daily User's Need (MWh/Day)	26.78
Maximum User's Power MW	1.41
Solar Energy Production (MWh/Year)	13785
Solar Energy Production (MWh/Day)	38
Power Produce by One Hour (MW)	6
Maximum Power Needed to Direct Use For 6 Hour (MW)	8.46
Energy Needed for Batteries Charge (MWh/Day)	18.32
Extra Production Energy (MWh /Day)	11.22
Total Surplus Energy (MWh/Year)	4095
Module Type	Monocrystalline silicon.
Inverter Type	High-efficiency central inverters.
System Configuration	Optimal tilt and azimuth angles, minimal shading.

Besides energy yield, PVsyst is also offering a loss in more details shown in Table 5. The highest single loss is associated with high temperature of modules that minimizes energy by approximately 6.6 % compared to an ideal reference. The battery round-trip losses add an additional 5.5% and the ohmic and mismatch losses are slightly above 2 %. Effects of incidence angle modifier and inverter losses are not very large. These findings affirm that two most significant levers to the further performance improvement in the system are thermal management and storage efficiency, and it is also possible to state that a PV/T cooling concept has important role included in the design and highlighting the significant impact of thermal conditions on PV performance[39].

Table 5. Loss details analysis

Loss Component	Value (%)
IAM factor on global	-1.9
PV loss due to irradiance level	-0.4
PV loss due to temperature	-6.6
Module quality loss	0.8
Mismatch loss (modules and strings)	-2.1
Ohmic wiring loss	-2.1
Inverter loss during operation	-1.2
Battery loss	-5.5
Loss with respect to optimum	0.0

The performance of the integrated photovoltaic (PV) system is assessed through key parameters, including the daily input/output diagram, and the relationship between array temperature and effective irradiance, shown in Figures 6 (a) & (b). The daily input/output diagram is crucial for understanding the energy flow and efficiency of PV systems, as it helps in assessing the energy yield and performance ratio, which are essential for financial viability and reliable electricity deliveries [40].These metrics provide valuable insights into the system's efficiency and effectiveness in energy conservation within industrial settings, particularly in powering ACs. The daily input/output diagram illustrates fluctuations in energy production and consumption over a typical day, highlighting peak solar generation periods that align with air compressor demands.



Figures 6. daily input/output diagram and array temperature vs. effective irradiance

Additionally, the integration of battery energy storage systems can optimize performance by storing excess energy during peak production times and releasing it during low irradiance periods, thus stabilizing output power distribution [41]. This synchronization optimizes energy utilization, ensuring that the highest energy demand is met with maximum solar output. Additionally, the analysis of array temperature versus effective irradiance reveals a clear correlation between higher irradiance levels and increased array temperatures, as supported by multiple studies. In photovoltaic (PV) systems, module temperature is significantly influenced by irradiance levels, with increased irradiance leading to higher temperatures. This relationship is crucial as it directly impacts the efficiency and power output of PV arrays. Research has shown that as solar insolation increases, so do the maximum output power, short-circuit current, and efficiency of PV panels, despite the concurrent rise in panel temperature due to the correlation between irradiance and temperature [42]. Empirical studies also confirm this, demonstrating that module temperature increases as irradiance rises [43]. This temperature rise impacts system efficiency due to thermal losses Elevated temperatures lead to a decrease in the open-circuit voltage and an increase in the short-circuit current, which collectively reduce the overall efficiency of PV panels [44], emphasizing the need for effective thermal management solutions. To enhance efficiency, utilizing a PV/T hybrid cooling system to circulate water and dissipate excess heat from PV panels can effectively lower their operating temperature from 35°C to an optimal 30°C, leading to a significant improvement in energy conversion efficiency. A study has demonstrated that surface cooling can reduce panel temperatures from 65°C to 42°C, resulting in a 10% increase in load voltage and an 18% increase in load power[45]. This emphasizes the potential of hybrid cooling systems PV/T in enhancing the performance and efficiency of solar PV systems, particularly in high-temperature environments. By maintaining optimal operating conditions, this approach mitigates thermal losses and enhances the overall system performance in supporting air compressor operations.

3.4. Energy balance between PV generation and compressor load

The PV system-compressor load energy balance is also at the center of determining the feasibility of the proposed integration. The compressors will need 9,690 MWh over a period of one year, whereas the PV system will produce 13,785 MWh during the same period. The surplus of 4,095 MWh is equivalent to 29.7 % compared to the PV production. The plot (Figure 7) of the annual PV generation versus compressor consumption in each company indicates that the aggregate PV output is comfortably more than the sum of compressor demand.

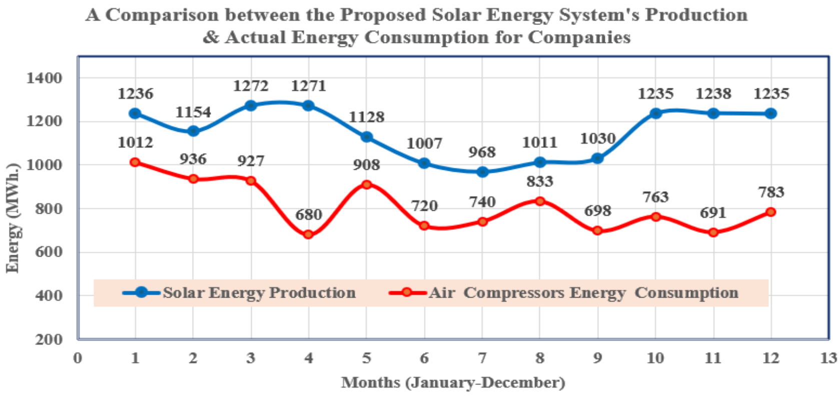


Figure 7. Proposed solar energy system's production vs. actual energy consumption for companies

The average compressor energy need is 26.78 MWh/day on a daily basis, as compared to the 38 MWh/day of PV generation. The surplus 11.22 of 11.22 MWh/day could be utilized in charging the batteries, that is, supplying other industrial loads or could be exported to the internal grid. The peak instant compressor base is 1.41 MW but under favorable conditions the PV system has the ability to produce up to approximately 6 MW of AC power. This power margin will enhance flexibility in the operations and could also tolerate short-term variations in the usage of compressors without necessarily reducing PV output.

It is the combined PV and battery system thus serving two purposes. The first one is that it entirely satisfies the energy requirements of the compressed air systems per year rendering them solar powered. Second, it generates a useful surplus that enhances the economics of the investment particularly in an environment where alternative sources of electricity are costly diesel generators. The balance will also indicate that the PV system has not been undersized but rather it is sized to meet the compressors and the other loads, which will be in line with the goal of maximizing the use of the available industrial roofs and land.

3.5. Impact of preventive maintenance on compressor performance

Preventive maintenance and repair of leaks affected compressor performance significantly. Using a well-organized programme of leakage sealing, changing filters and optimizing the control was able to reduce the overall compressor power usage to 1,929 MWh/year. Due to the large size of the companies and the nature of their industrial operations, leak control measures were able to reduce the total energy loss resulting from them by 85% of losing energy due to air leaking. The comparison of before and after is shown in Figure 8 in individual companies. There are improvements in all the factories, with the greatest absolute savings in the dairy and sponge and plastics plants which were the largest consumers.

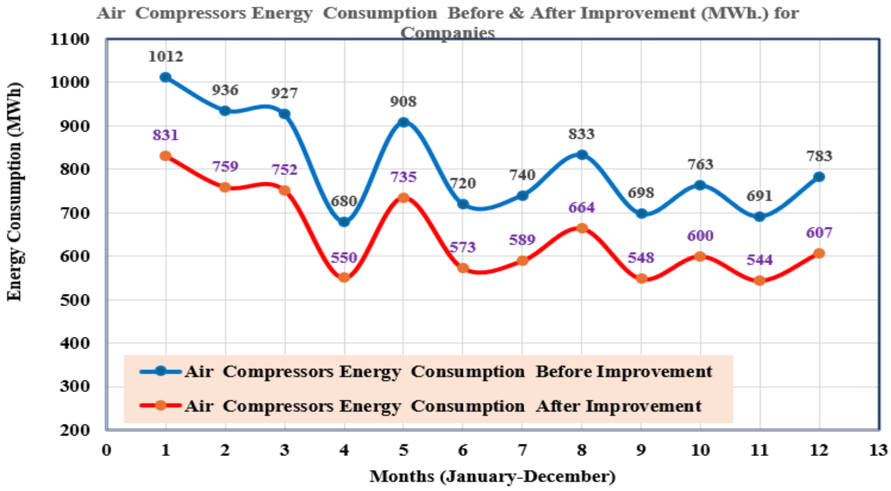


Figure 8. Air compressors energy consumption before & after improvement (MWh.) for companies

In the compressed air view, the reduction in the volume of leakage reduced the proportion of lost energy to leakages to a significantly lower value, but some leakage cannot be avoided. Meanwhile, the new control strategy minimized idle running and unload operation, i.e. compressors now run closer to the real demand. Consequently, the certain energy usage of the compressed air systems was enhanced, and the load profile was somewhat flatter. These systems, which manage motor operation and air pressure based on real-time measurements and demand , have been shown to reduce electricity costs by 20-30% by minimizing unnecessary operation time [46]. This approach aligns with the findings from a case study in pharmaceutical packaging manufacturing, which demonstrated a 23% reduction in compressor electricity usage and a 7-8% decrease in compressed air consumption. These savings were achieved through the reduction of air leaks and the optimization of compressor performance [4]. These advancements underline the significant impact of control systems in improving the efficiency of compressor operations, reducing overall energy consumption, and supporting demand response strategies.

The integration of control systems further optimized energy use, shifting air compressor operation based on actual demand and preventing unnecessary consumption. These improvements not only reduced operational costs but also contributed to environmental sustainability by lowering energy consumption and greenhouse gas emissions [37]. There are two implications for these changes. To begin with, they directly save on electricity expenses, whether the source of power supply is found. Second, they affect the optimal design of the PV system: by designing the PV array to meet the lower demand, instead of a wasteful baseline, one will achieve savings in over-sizing and achieve a better cost effectiveness of the combined solution. The maintenance programme is thus a low cost complement to the PV investment, that improves both the technical and economic performance.

3.6. Economic analysis

The economic analysis would compare the profitability of 7 MW PV system compared to two scenarios of the price of electricity, one situation in Yemen where tariffs are high, and another situation in the global markets where average prices are low. The most important financial parameters are summarized in Table 6. The initial investment amount is 12,738,940 USD which includes PV modules, inverters, mounting structures, batteries as well as balance of system. This is 13,785 MWh per annum of PV energy production. Using 0.40 USD /kWh as the value of electricity, which is representative of the cost of self-generation with diesel in Yemen, the gross revenue of the displaced electricity is approximately 5.514 million USD/year. The initial return on investment is approximately 43 owing to an annual operation and maintenance cost of 25,000 USD that is subtracted.

In a 30 year project life under the assumption of 1% per annum degradation in energy yield the total ROI is approximately 1,021, and the simple payback time is approximately 2.3 years. The total revenue in the project life is projected to be 130 million USD. The figures show that there is a very appealing investment in local conditions due to the high replacement cost of conventional electricity. The fact that the PV system also provides excess energy over and above the compressor demand is another added advantage to the financial case since the excess power can be used in other loads or minimize the running time of the generators.

In the global context, where the theoretical price of electricity is 0.10 USD/kWh, the net revenue will reduce to approximately 1.354 million USD/year. The first ROI reduces to 11 per cent and the payback period increases to approximately 9.4 years. The overall payback period is about 252 formula in 30 years, and the overall revenue is nearly 32 million USD. These results are not as impressive as in the Yemeni case, but they still prove the fact that the system is still financially viable in markets where electricity prices are moderate.

It should be mentioned that these economic indicators are susceptible to a number of assumptions namely the value of displaced electricity, the real compressor demand with time and the realized PV performance ratio. With the soaring fuel prices, the cost avoided per kilowatt hour will go up; hence, reducing the payback period even further. On the other hand, when compressor operating hours go down or electricity tariffs go down, the financial measurements would be weak, but the project would still enjoy very low operating costs and long life of the assets. Practically, because of high local tariffs and high load factors in Taiz, the suggested system is particularly favorable.

Table 6. Economic viability parameters and main findings of the proposed system

Parameters	Yemen average cost ($0.40/kWh)	International average cost ($0.10/kWh)
Initial Investment	$12,738,940	$12,738,940
Annual Production Capacity	13785 MWh	13785 MWh
Electricity Price	$0.40 per kWh	$0.10 per kWh
Annual Operational cost	$25000	$25000
Annual Net Revenue	$5,489,000	$1,353,500
Initial ROI	43%	11%
Annual Degradation	1%	1%
Total ROI (30 years)	1021%	252%
Payback Period	2.3 years	9.4 years
Cumulative Revenue (30 years)	$130,041,289	$32,066,111

3.7. Environmental impact assessment

The integration of solar photovoltaic (PV) systems offers significant environmental benefits, primarily by reducing carbon emissions and minimizing reliance on fossil fuels[47]. The project was evaluated in terms of avoiding carbon dioxide emission with regard to environmental performance. Based on a grid or diesel emission factor of 640 g CO 2/kWh, the PV generated electricity of 13,785 MWh in one year is equivalent to a CO 2 saving of approximately 8,822 tons in one year. The cumulative CO 2 savings of 229, 647 tons are achieved when 1 percent of the degradation of these sources is compounded in 30 years. PVsyst approximates that the amount of CO 2 emitted by the production of the PV modules, inverters and mounting structures is approximately 108.9 tons. The net reduction of the emission is thus about 229,538 tons over the life of the system as shown in Figure 9.

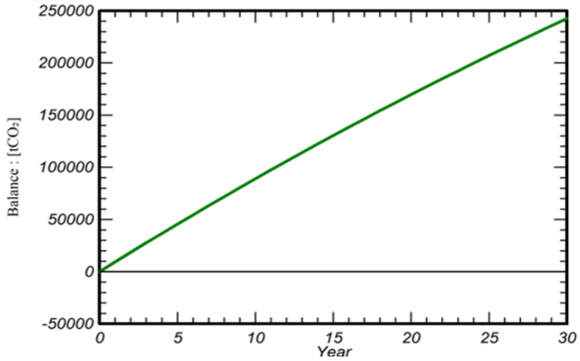


Figure 9. Environmental impact (PV syst)

The findings of the current study are supported by several studies that demonstrate the significant impact of large-scale integration of solar PV systems on reducing carbon emissions. In regions such as California and the Southwest United States, the widespread deployment of solar PV has led to notable reductions in carbon emissions, underscoring the importance of policy measures to further enhance these benefits in other areas[48]. Similarly, a proposed solar PV station in Jordan has been shown to reduce annual greenhouse gas emissions by 89% compared to conventional oil stations, illustrating the significant potential of solar PV in mitigating climate change[49].

The integration of solar photovoltaic (PV) systems is increasingly recognized as a critical component in the global transition to renewable energy, offering a sustainable solution to reduce carbon emissions and decrease reliance on fossil fuels across various sectors [50, 51] . Solar PV systems play a crucial role in fostering a sustainable energy future by significantly reducing reliance on fossil fuels. Their implementation not only enhances energy security but also stimulates innovation within the green technology market [52]. The transition to solar PV systems is essential for achieving global climate goals, as it creates a resilient and sustainable energy infrastructure capable of adapting to future challenges [53]. Additionally, this analysis underscores the environmental sustainability of the PV system, demonstrating that the CO_2 emissions saved by replacing conventional power generation methods far exceed the emissions generated during the system's lifecycle, reinforcing its pivotal role in climate change mitigation. In the case of the industrial zone, the project will greatly lower the intensity of production carbon, which may be crucial to export-based businesses that have to grapple with growing demands of environmental reporting.

On a national level, the mass imitation of these PV-compressor types in other industrial regions may be a significant contribution towards the Yemeni climate and energy targets albeit in the presently weak state of electricity. The systems also have co-benefits in worker health and urban air quality since they cause a reduction in local air pollutants and noise, because the systems displace diesel generation.

3.8. Comparative discussion with previous studies

The Yemeni system has competitive or better technical performance when compared to other similar 7 MW PV projects reported in the literature. The simulated 81% performance ratio is a little lower than the 83 percent of a Libyan hospital PV plant [27], but higher than the simulated and measured PR of 79.5 and 70.8 % respectively of the Malbaza PV plant in Niger [31], This aligns with the general understanding that a PR above 80% is considered efficient for PV systems, as it reflects well-optimized system design and operation [5]. The annual yield of the particular place is also not out of the range of high-irradiance sites. These similarities imply that the design assumption made in PVsyst are decent and that Taiz climate is well adapted to the large PV plants.

Conceptually speaking, the surplus share of 29.7 % is similar to Thai 7 MW PV plus battery project, in which storage can enable 7 MW of PV to essentially supply all industrial demand [30]. The Yemeni system, in its turn, is based on a less complex storage plan and absorbs the excess energy with the help of the industrial grid, which might be more realistic in the context when there are few technical means. The 20 % decrease in compressor energy as a result of maintenance and control on the compressed air side is favorable to the published case studies of 20 to 30 % reduction through fixing leaks and optimized control.

The added value of a conceptual PV/T effect is based on better thermal management , since the simulation shows that improved cooling will allow reducing the temperature loss of 6.6% identified in the loss diagram, and the performance ratio will move towards the higher end of the range observed in other similar plants. which confirmed the importance of added PV/T to the system.

Overall, the findings confirm that the Yemeni case is technically aligned with the international practice in the PV performance and compressed air optimization and contributes to the additional evidence of large-scale integration in a weak grid setting. The synergistic real data of industrial compressors measured leakage reduction and the extensive PV simulation makes this work unique among most of the previous works which either uses generic load profiles or concentrates on the PV plant instead of end-use efficiency.

3.9. Key findings and interpretation

This study revealed that a 7 MW solar PV system installed and combined with preventive maintenance of industrial air compressors can bring significant upturn in energy consumption and cost reduction in the Al-Huban industrial zone in Taiz. The analysis of the base line revealed that compressors consumed 9,690 MWh/year, or 16 % of the plant electricity with approximately 2,269 MWh/year going to waste. The compression electricity use was decreased by 20% through leakage repair and control optimization, which saved 1,929 MWh/year and decreased the ratio of energy wasted.

The optimized PV system installed at a 17.5° tilt generated 13785, which is equivalent to 13785 MWh/year of supply to the compressor, and 4095 MWh of excess supply. The simulated performance ratio of 81% and the breakdown of losses show that the system is running effectively and that the primary opportunities for improvement are temperature, battery and wiring losses. The daily and annual energy balance testifies that the PV plant will be able to supply the compressors consistently, as well as attend to other industrial loads.

The project has very high viability economically in the high cost of electricity in the Yemen market, where the payback period is approximately 2.3 years and the ROI is more than 1,000 %. The investment is still attractive even at lower prices of international electricity. The environmental impact of the PV system would prevent close to 230,000 tons of CO 2 in 30 years, including the emissions of the life cycle of the PV system, so the local and global climate goals.

In the case of the industrial sector in Yemen, these results suggest that specific efficiency increases in compressed air systems, coupled with properly planned PV plants, can turn out to be considerable influence on the reliance upon diesel generation, stabilize production and release financial resources to the other investments. On a larger scale, the strategy offers a template that can be applied in other countries experiencing the same dilemma of high fuel prices, and unstable power supply in industrial estates. It is therefore not only that the study fills a research gap that has been identified and established on Taiz Al-Huban but also can provide realistic advice to engineers, factory managers as well as policy makers who are looking to the same interventions in a similar environment.

4. Conclusions

This paper aimed to determine whether a large-scale solar PV park, with specific focus on efficiency interventions on industrial air compressors, can be reliably used to service the compressor loads and save energy expenses in an unreliable-grid setting like Taiz Al-Huban, Yemen. The outcomes prove the fact that this goal has been accomplished on technical, economical, and environmental levels.

4.1. Summary of key findings

It was built on the integrated system of a 7 MWp PV plant developed with real industrial data of five factories and simulated in PVsyst. The plant has a power output of 13,785 MWh/year and the compressors need 9,690

MWh/year, and hence the PV system has the capacity of producing all the electricity needed by the compressors, and its excess is 4,095 MWh/year, which is 29.7 of the PV output. The simulated performance ratio (PR) of 81 % is comparable to utility-scale plants in similar climates which perform well, and this suggests that the losses during the design are under control.

On demand side, 851 leakage points were found, and 18.9 million m³ of leakage per year was identified, representing 2269 MWh/y of wasted electricity. The leak repair and preventive maintenance, as well as the enhanced compressor control, led to a decrease in the electricity consumption by compressors by 1,929 MWh/year, which is 20% lower than the baseline. Such measures decreased the percentage of energy wasted on leakage and minimized the specific energy use of the compressed air systems.

With an initial investment amounting to 12.74 million USD, the project will generate an initial ROI of approximately 43 % and a payback period of approximately 2.3 years at a rate of 0.40 USD/kWh, which is equivalent to the rate of diesel-produced supply in Yemen. With 1 percent PV degradation per annum over 30 years, the cumulative ROI is more than 1,000 percent and cumulative revenues are approximately 130 million USD. The system is also feasible at a lower international electricity price of 0.10 USD/kWh with a ROI of 252 and a payback period of approximately 9.4 years.

Concerning the ecology, the PV system can prevent some 229,647 tons of CO 2 in 30 years, when the performance deterioration is taken into consideration. The calculated amount of CO 2 reduction would be approximately 229,538 tons by subtracting the estimated amount of 108.9 tons of CO 2 in the PV components. These values show that there is a high climate benefit besides cost savings.

Lastly, the tilt-angle optimization found that 17.5° was the optimal fixed angle of Taiz, and it yielded higher energy per annum than a horizontal array and confirmed the application of site-specific design to industrial PV plants. Conceptual introduction of PV/T cooling cools down cells, and contains losses associated with temperature, which constitute 6.6 percent of potential yield; the largest single loss contribution.

4.2. Contributions and industrial significance

The key value of the work is showing, on the basis of measured industrial data, that the integration of solar PV can completely cover the electricity needs of large industrial compressor systems in Yemen with a short payback period, and, at the same time, enhance the efficiency of compressors, reducing leakage and other types of preventive maintenance. In comparison with the past 7 MW PV research, the present work is unique in three senses:

- It, at scale 7 MW PV design with leakage quantified to the minute and compressor operation measured in large factories (5), of scale, instead of using generic or assumed load profiles.
- It combines demand-side optimization (20 % compressor energy) and supply-side PV optimization (PR 81%, tilt 17.5 degrees) into a single coherent framework.
- It has a PV/T performance improvement concept in the performance analysis, with specific reference to the connection of the thermal conditions to the electrical yield as well as the temperature control as well as the design lever.

The findings are of great importance to industrial firms which are working in unstable-grid conditions. The paper demonstrates that a PV system well scaled can not only stabilize the supply of critical compressed air systems, but also greatly reduce the cost of fuels as well as the risk of fuel price fluctuations. The excess energy that will be generated by the PV plant can serve other loads or decrease the time of use in the generator, which increases overall resilience of the plant. This will mean to the owners of factories reduced operating cost, enhanced dependability of output, and a measurable decreased carbon footprint of their products.

4.3. Limitations

There are several limitations that should be taken into consideration. First, the performance of PVs is only simulated but not measured over a long period; even though the PVsyst is an established software and the findings are consistent with other projects of the same nature, the actual performance of PVs can vary under soiling conditions, maintenance behaviors, and unexpected physical degradation. Second, there is no detailed cycle-by-cycle ageing model, but only conventional efficiency and degradation considerations of the battery system. This implies that the issue of battery replacement schedules and its effects on economics are not completely addressed in the long term. Third, PV/T effect is modeled with modified thermal coefficients instead of a complete modelled fluid system and thus the quantitative analysis of cooling benefits is only approximate. Lastly, the compressor demand profiles relied on one year of data; any major shift in production would modify the demand or introduction of new equipment, and this would adjust the load and hence the PV size would change accordingly.

4.4. Recommendations and future work

Three useful suggestions come out to industries that are thinking about using similar systems:

1. Begin with compressed air efficiency: the companies need to conduct leak detection, general maintenance, and control optimization originally before and/or concurrent to the installation of PV. The energy saving of 20 % in this case demonstrates that the cost-effective solutions can greatly decrease the necessary PV capacity and enhance the economics of the project.
2. Select site-specific PV design and performance simulation: tilt-angle optimization, realistic PR assumptions, and the incorporation of storage or backup are each critical to plausible economic analysis, in situations where electricity is generated by high price diesel.
3. Introduce monitoring on the initial stage: serious metering of compressor energy, pressure, and PV production will assist in sustaining the performance gains and facilitate the constant improvement.

The shortcomings of the analysis and the analysis itself could be tackled in future work in a number of ways. The implementation of advanced battery energy storage system (BESS) optimization, such as detailed cycling models, dynamic dispatch strategies, and possible involvement in demand response is one of the priorities. The other is the adoption of real-time monitoring and control through Internet of Things implementation, which connects the PV generation, compressor load, leakage detention and battery management on one platform to optimize the system at minute-by-minute level. Also, the field validation of PV/T cooling strategies in the conditions of Yemen over the long term would be useful in measuring the actual electrical gain and improving the loss model. Lastly, it would be possible to broaden the analysis to other important industrial loads (including refrigeration, motors, and process heating) to have a more holistic design of renewable-powered industrial parks.

Overall, this paper has shown that a mix of large-scale solar PV and specific measures on compressed air efficiency can provide stable power, fast payback, and substantial emissions reduction of industrial areas in developing nations. It offers a viable and repeatable roadmap to sustainable and solar-powered industrialized energy in delicate and fuel-starved settings such as Yemen.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Wael. Author, Mohd. Author and Mokhtar. Author: study conception and design; Wael. Author, Jagadeesh. Author and Mokhtar. Author: data collection; Wael. Author, Mohd. Author. Johnny. Author: analysis and interpretation of results; Wael. Author, Mohd. Author and Mokhtar: draft preparation. All authors approved the final version of the manuscript.

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