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Energy efficient dry-storage systems in the semiconductor manufacturing industry

Daniel Frendo[a,b], Paul Refalo[c]*, Robert N. Farrugia[b], Noel Balzan[a]

[a]*STMicroelectronics Malta Ltd, Industry Road, Kirkop, KKP9042, Malta*
[b]*Institute for Sustainable Energy, University of Malta, Marsaxlokk, MXK1531, Malta*
[c]*Department of Industrial and Manufacturing Engineering, Faculty of Engineering, University of Malta, Msida MSD2080, Malta*

Abstract

The semiconductor industry is a rapidly-changing one and many new electronic devices are being developed every year. As components get smaller and thinner, humidity-related problems increase since moisture can easily penetrate to critical areas. There are various techniques to prevent moisture ingress during manufacturing and assembly. One of the best methods is to store semiconductor devices in dry storage enclosures (also known as Dry Boxes) between consequent processes and operations. However, since they are typically supplied with Compressed Dry Air (CDA), Dry Boxes tend to be energy intensive. By using an industrial setup at a manufacturing facility in Malta as a case study, an empirical assessment was carried out to investigate the use of Dry Boxes from an energy consumption perspective. The energy performance of Dry Boxes using CDA was compared to that of Dry Boxes using a desiccant-rotor technology. The relative humidity and air temperature inside the Dry Box were monitored in order to assess the behaviour of both technologies with time. An analysis of the Dry Box conditions was conducted to better understand the sources of any existing losses and to identify whether scope for improvement, if any, existed. The study showed that even if the drying technology on the supply side is not changed, improvements on the demand side can have an effective reduction in resource consumption. Using the desiccant rotor instead of CDA to dehumidify the Dry Box did not decrease the energy consumption. However, it was positively concluded that by reducing the infiltration rate and the unoccupied internal volume of the Dry Box, the CDA consumption and hence the energy and carbon footprint of the process decreased by 26%, contributing towards the sustainability goals of the manufacturing industry.

Keywords: sustainable manufacturing; energy efficiency; semiconductor industry; Dry Boxes; Compressed Dry Air (CDA).

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* Corresponding author. Tel.: +356 2340 2058
E-mail address: paul.refalo@um.edu.mt

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1. Introduction

Shockley, Bardeen and Brattain invented the first transistor in 1948 and the subsequent development of the Integrated Circuit (IC) in 1958 marked the beginning of rapid progress in the semiconductor industry. [1]. Following this invention, an era of consecutive successful improvements in the semiconductor industry was triggered. In 1965 Gordon Moore projected that the number of transistors per IC will have an exponential growth, doubling every one-and-a-half to two years [2]. In fact, this observation is known as Moore's Law and has become the leading principle in the semiconductor industry. Today's technology depends on the IC, which is the heart of the semiconductor industry. One can say that electronic chips control practically everything, from wireless networks to computers, automobile electronic control units, smart watches, wind turbines, household applications and rockets. An IC consists of a collection of memory storage devices and transistors which are switched on or off by means of an electrical signal carried through interconnecting wires. In the last few decades, the semiconductor industry has progressed rapidly and has the ability to match the ever-increasing demand for higher functionality, smaller size, speed and portability [3].

The semiconductor industry has encountered various challenges, including the lead-free initiative to reduce hazardous substances in electronic products. The lead-free challenge is driven by market advantages, government legislation and environmental concerns [4]. The removal of lead from semiconductor devices forced manufacturers to increase temperatures during some of the manufacturing processes, making the devices more susceptible to moisture-related issues. High humidity can cause water layer formation, leading to failures and reliability issues such as crackling, bond cratering, bond lifting, wire necking, pop corning, delamination, dendrite growth, oxidation, short circuits, and high leakage currents. Approximately 23% of electronic failures are attributed to humidity contamination. In fact, manufacturers are investing in humidity protection to mitigate these defects, which have significant financial consequences. Some of these mitigation techniques include dry packaging, die sealing, passivation layers, baking, and storing semiconductor devices in Dry Boxes between consequent assembly processes and operations [5]. The design of semiconductor devices has been altered in various ways to combat moisture issues. Some of these modifications include an additional top layer to prevent moisture ingress, seals around the perimeter of the die, closing the semiconductor in hermetic bags, and storing semiconductor devices in a Dry Box that uses powerful desiccant material or Nitrogen (N_2) to create a dry environment. Concurrently, the semiconductor industry is also driven to be as carbon neutral as possible, as manufacturers are pushing to reduce energy consumption in order to remain competitive, while reducing the carbon footprint of the produced devices.

This study investigates the effectiveness of Dry Boxes in preventing moisture ingress during manufacturing and assembly from an energy consumption perspective. The aim of the experiments was to assess simple and practical improvements in the design and operation of the Dry Box while comparing two drying techniques under various conditions. A sustainable and practical approach to reduce the energy consumption and the associated carbon footprint of semiconductor manufacturers is hereby presented and evaluated.

Nomenclature

IC	Integrated Circuit
N_2	Nitrogen
CDA	Compressed Dry Air
RH	Relative Humidity

2. Moisture mitigation techniques

As the level of IC failures due to moisture sensitivity increases, manufacturers are investing more money and time to safeguard semiconductor device assembly lines [6]. Various mitigation techniques are currently being used to combat moisture absorption from the environment. Semiconductor device assemblers have adopted a common strategy which involves storing the devices in Dry Boxes between subsequent processes and operations. Dry Boxes maintain internal conditions at relative humidity (RH) levels lower than 10% and temperatures below 30°C. However, in order to allow such low RH levels in an active environment, manufacturers supply the Dry Boxes with high flow rates of dry gases, typically Nitrogen or treated CDA [7]. Figure 1 shows a typical Dry Box used in the semiconductor industry. Nitrogen is very abundant in nature, making up to 78% of the earth's atmosphere [8]. It is an odourless, tasteless, colourless, dry and non-combustible, making its properties identical to those of a completely inert noble gas [9, 10]. Being dry and non-combustible, N_2 purging has numerous benefits for industrial use. It is very effective in preventing moisture-related damage, combustion, oxidation and chemical alteration of products [11]. However, it can be hazardous in confined spaces and it is expensive to produce [12].

Figure 1: Typical Dry Box used in the semiconductor industry [13].

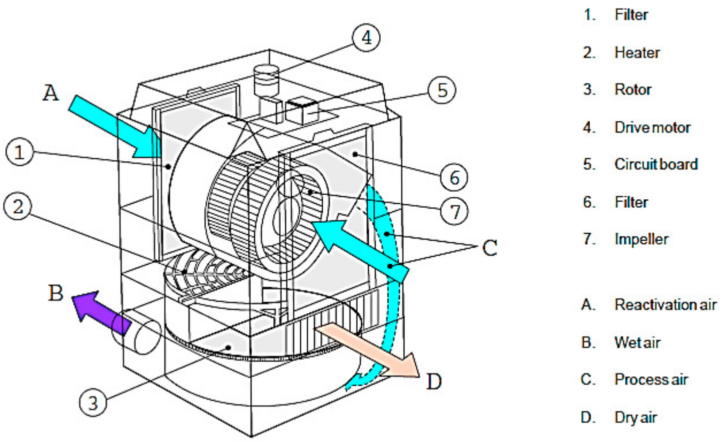

Figure 2: Detailed schematic of the working principle of a desiccant rotor [14].

Due to the high initial and operational costs to generate N_2, manufacturers use alternative solutions to create low RH storage systems, while still remaining competitive. For this reason, N_2 is being phased out in favour of dry air for the storage of semiconductor devices [15]. The composition of atmospheric air comprises contaminants of unwanted water vapour, particles and gases. The concentration of these contaminants varies, depending on the location of nearby sources and time. The composition of contaminants in compressed air systems is contingent upon the specific utilization of the air, leading to the existence of diverse compressed air standards tailored for different industries. For microelectronics manufacturers, high production yields depend on clean dry air since semiconductor devices are stored in Dry Boxes between processes to reduce the moisture intake. Also, CDA is a must for such boxes since small amounts of oil aerosols and particulate contamination can cause bridging and short-circuits in the microcircuits [15].

Various drying technologies are available on the market, of which adsorption by a desiccant material is the most utilized in the semiconductor industry since very low dew point temperatures must be achieved. A desiccant material is a dehumidifying agent which has high levels of affinity towards water. Dual beds and rotor dryers are mainly utilised when opting for desiccant materials. For continuous operations, a typical dual bed system consists of a dual tower design which simultaneously performs on-line drying and off-line regeneration. The drying tower consists of a vessel containing a porous hygroscopic material which inhibits water molecules as compressed air passes from the bottom through the desiccant material and exists from the top part of the dryer [16, 17]. On the other hand, desiccant rotor dryers can be used directly at the point of use, adjacent to the Dry Box itself. This approach eliminates the need for compressors, cooling towers, dryers, and micro filtration typically used in generating dry air and performing regeneration. As a result, the proposed air-drying technique does not use the mentioned equipment. The Dry Boxes serving as the storage system for the specific products, remain unchanged. Figure 2 provides a visual representation of the working principle of the rotor dryer. Unlike conventional desiccant dryers, a rotor dryer uses only a desiccant wheel which is made from composite materials that are highly effective in retaining and attracting water vapour and it is composed of solid desiccant which is coated, formed, or impregnated in place on the rotor structure. Notably, this unit requires solely an electrical power supply to operate the desiccant wheel, heater and blower [16, 17].

3. Case Study Description

A semiconductor manufacturer, namely STMicroelectronics Malta (STM), uses Dry Boxes to store its products in a dry environment to prevent the absorption of moisture between processes. The Dry Boxes are installed in a Clean Room environment, which is a highly controlled area designed to maintain low levels of airborne particles, contaminants, as well as precise temperature and relative humidity conditions. A Dry Box installed in a real industrial environment at STM was used as a case study. This study assessed the effects of various improvements which can be carried out on the design and operation of Dry Boxes on air and energy consumption. Additionally, the effect of changing the current drying technology was also assessed. The benefits and drawbacks in terms of sustainability and quality of the dry air generated will be assessed by comparing the currently-used method to adoption of a newer drying technology.

The company uses a large scale industrial compressed air supply system which meets the plant's pneumatic demands. The process starts by compressing ambient air and storing it in a buffer tank. During compression, a substantial amount of heat energy is generated and therefore the compressors must be cooled. Cooling towers are used to provide the necessary cooling. The compressed air is then conveyed through dryers to reduce the water vapour content, hence achieving the desired dew point. Humidity absorption is achieved by means of a desiccant material using a dual bed technology and desiccant regeneration is performed by heated purge regeneration. Since dual-bed technology is used, after 6 hours of air drying, the bed will be automatically changed, and regeneration will be performed for the next 6 hours. This process is automated, and each cycle is repeated every 6 hours. Prior to being conveyed to the Dry Boxes, the CDA flows through micron filters to remove any particles which might have been picked up during the absorption cycle. Figure 3 illustrates a schematic showing the complete cycle of CDA from the point of generation until the point of use in the Dry Boxes.

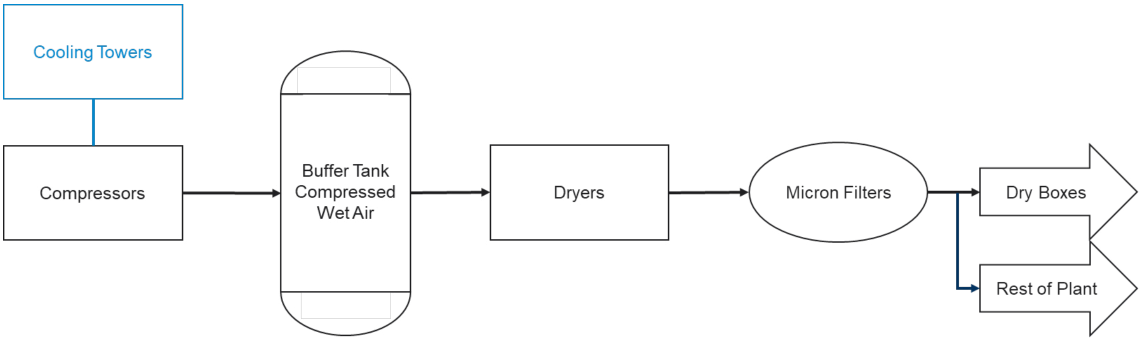

Figure 3: A schematic showing the complete cycle of compressed dry air generation until distribution in Dry Boxes.

The pneumatic system supplies compressed air at a pressure of 7 bar. The typical dimensions of a Dry Box are shown in Figure 4 (a). In order to reduce CDA consumption, the dry air supply is automatically switched off when the required RH level inside a specific Dry Box is reached. Air temperature and RH sensors are installed inside each Dry Box as shown in Figure 4 (b). These sensors control a solenoid valve which, when open, allows CDA to be supplied to the Dry Box. Since electronic products are typically stored in a dry environment with RH levels lower than 10%, a control board triggers the supply of CDA once the RH levels within the Dry Box exceed 8%. The CDA supply is then shut off once RH levels drop below 6%. The benefits of such an air-drying technique include:

- very low dew points can be achieved;

- a relatively low storage temperature can be maintained;
- does not require use of chemicals.

However, such an air-drying system has the following drawbacks:

- on average, 25% of the generated compressed air is typically wasted due to leakages [18];
- the dryer's bed consists of a huge surface area, therefore requiring bigger and stronger blowers to dissipate heat and have an effective regeneration process [19];
- spikes in dew point temperature could occur during drying bed changeover [19];
- use of a centralized system which requires pipework to supply the shop floor equipment. Also, if one component fails, all production will have to be stopped, resulting in undesirable production losses.

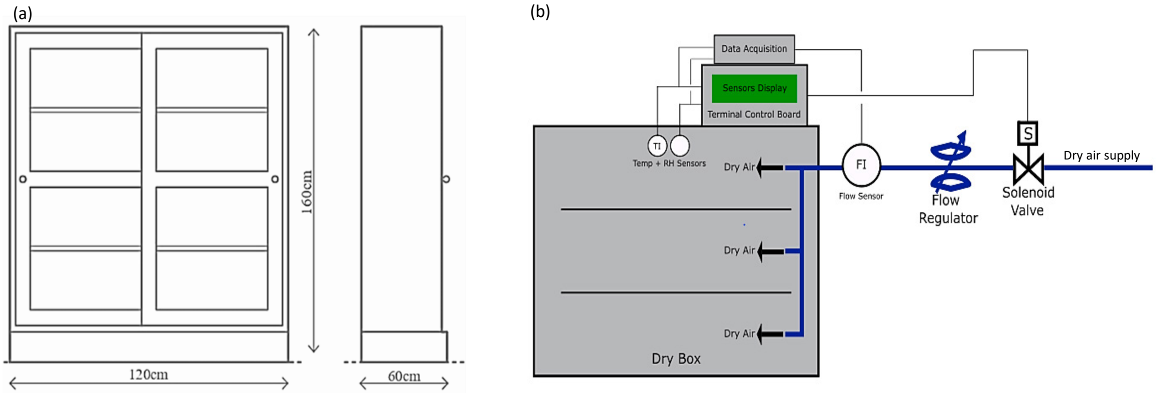

Figure 4: Schematic showing (a) typical dimensions of a Dry Box [20] and (b) the CDA supply to the Dry Box.

4. Experimental Methodology

The Dry Box used in this study had a total internal volume of 1.15 m^3. The enclosure comprised melamine boards for the sides, back, top and base slotted within an aluminium frame and had three internal compartments separated by two shelves. The Dry Box can be accessed by opening either of the two frontal glazed sliding doors which also enable external viewing of the cabinet contents. In opening one of the sliding doors, half the frontal area of the Dry Box is open to the Clean Room environment. The aim of the design of experiment was to assess simple and practical improvements in the design and operation of the Dry Boxes being used at STM and to compare both drying technologies under different circumstances. By monitoring the temperature, RH and flowrate of the CDA within the enclosure, the specific energy consumption for each test could be calculated. The below four variables were taken into consideration when formulating the design of experiment:

1. Dry Box access (glazed sliding door Opening/Closing cycles);
2. Dry Box interaction with the Clean Room environment;
3. Dry Box unused internal volume;
4. Dry Box supplied with dry air from a desiccant rotor dryer.

4.1. Front Sliding Door Opening

In order to simulate a realistic production environment, one of the tests monitored the Dry Box with and without any glazed sliding door opening/closing cycles. This test was useful since it monitored the required amount of CDA when the sliding door of the Dry Box was opened to the ambient conditions of the Clean Room. Based upon observed utilisation rate, the opening/closing cycle rate was set at three (3) per hour, with one of the sliding doors kept fully open for one minute.

4.2. Dry Box interaction with the Clean Room environment

In order to maximize efficiency and reduce losses, one of the assessed improvements comprised sealing one of the two sliding doors to a fixed 'closed' configuration and also sealing the joints between the wood composite panels and the aluminium frame. These were completely sealed with aluminium adhesive tape to reduce ambient air infiltration inside the Dry Box. This test was based and divided on two levels, i.e., 'with' and 'without seal improvement'.

4.3. Dry Box Internal (Underutilized) Volume Reduction

This series of tests targeted the internal, underutilised volume of the Dry Box and studied the implications of retaining partially empty shelves as compared to artificially reducing the internal volume by inserting shelve 'fillers'. The main reason behind this was to minimize empty, i.e., unutilised storage space, thus reducing the required volume of dry air. This was done by filling the shelves of the Dry Box with closed, empty plastic boxes. This test was run on two levels which were 'with' and 'without internal volume reduction'.

4.4. Dry Box supplied with dry air from a desiccant rotor dryer

Further to the changes in the Dry Box itself, the drying technology was also changed and assessed. The objective here was to evaluate the effectiveness and efficiency of a desiccant rotor dryer compared to the current system which uses CDA. The rotor dryer was ducted to the Dry Box and tested on a potentially improved Dry Box. Therefore, the tests compared the energy consumption of both drying technologies, with all the improvements explained above also being implemented.

4.5. Design of Experiment

Table 1 shows the design of the experiment used for this study, where the focus was on evaluating the performance and efficiency of the Dry Box when the above-mentioned alterations were applied. The tests were held in a real operational environment.

Table 1: The design of experiment utilized for this study.

Test	Sealing	Volume Reduction	Open/Close	Dryer
1	No	No	No	CDA
2	No	No	Yes	CDA
3	No	Yes	No	CDA
4	No	Yes	Yes	CDA
5	Yes	No	No	CDA
6	Yes	No	Yes	CDA
7	Yes	Yes	No	CDA
8	Yes	Yes	Yes	CDA
9	Yes	Yes	Yes	Desiccant Rotor

4.6. Experimental Set-up

In the setup installation for testing purposes, as depicted in Figure 4(b), the temperature and RH sensors were installed in the middle section of the Dry Box. An LM35 precision temperature sensor was used to measure the temperature inside the Dry Box. The working temperature range of the LM35 series is from -55°C to 150°C with an accuracy of ±0.5°C at room temperature [21]. An HIH-4000 series humidity sensor was used to measure the RH levels inside the Dry Box. The accuracy of the sensor is of ±0.5% and is capable of measuring from 0% to 100% of RH [22]. Temperature and RH measurements are crucial for quality control and essential to analyze their relationship with energy consumption. Measuring the drying time to achieve and maintain the desired temperature and RH levels in the

Dry Box is also important. For Tests 1 to 8, the compressed air flowrate was measured using a VPFlowScope [23] which has an accuracy of 0.5%, and which was installed on the outer back surface of the Dry Box. In the case of the desiccant rotor dryer (Test 9), the electrical energy consumption of the dryer was monitored using a power logger [24]. The sensors were connected to a power supply and a National Instruments data acquisition system which was connected to a laptop to enable data storage. LabVIEW [25] was used to program the sensors and log the collected data. Each test was 2 hours long and was repeated three times.

5. Results and Discussion

In the above section, the design of experiment explained the various types of tests that were conducted. The results from Test 2, which was considered to be the benchmark and most realistic scenario, are presented in detail below. A comparison of all the results was carried out to assess the effectiveness of the alterations made to the Dry Box and of the alternative drying technology.

5.1. Results of Test 2 – Benchmark Scenario

This test consisted in utilizing the dual bed technology for the CDA supply and a Dry Box with no seal improvement, no internal volume reduction and with three sliding door opening/closing cycles per hour. This implies that the standard Dry Box was opened as per normal production procedure and that the increase in RH was a result of air infiltration due to leaks and due to the Dry Box sliding door opening cycles. The temperature varied between 20.8°C and 21.9°C, with an average of 21.4°C while the RH varied from 4.2% to 39.01%, with an average of 10.4%. As can be seen from Figure 5, the rise in the RH level was due to the infiltration of air from the Clean Room into the Dry Box (caused by leaks and the sliding door opening/closing cyclic action). It is evident that in the 2-hour timeframe, the sliding doors were opened six times, with a concurrent spike in RH (grey curve) and the simultaneous supply of CDA (blue curve). The supply of CDA resulted in a drop in RH, and once the threshold value was reached the CDA valve closed and hence the flowrate was shut off. In between the sliding door opening/closing cycles, vapour from the Clean Room infiltrates the Dry Box and hence the RH increases slowly. In two instances, the upper RH threshold was reached in between cycles, which hence triggered the CDA valve to open for a short period of time to supply the Dry Box with dry air and reduce the RH to the lower limit.

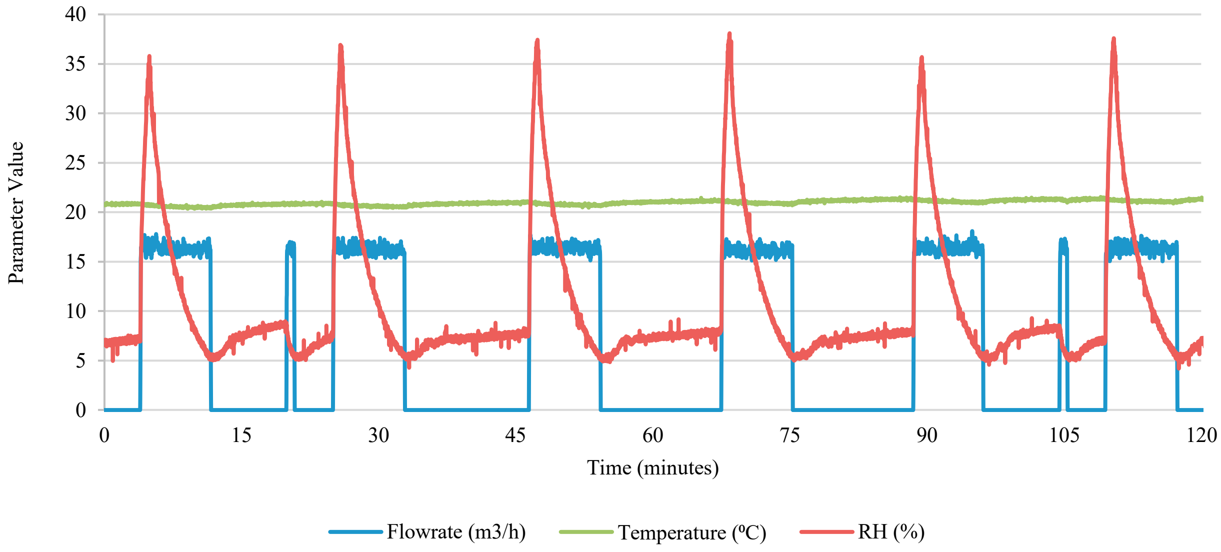

Figure 5: A Graph of Temperature, RH and CDA Flowrate vs Time (Test 2)

In this case, the average total volume consumption of CDA for the 2-hour test was of 17.3 Nm^3, (which includes 25% leaks attributed to the typical pneumatic losses in the compressed air system, from CDA production to the point-of-use). The specific energy consumption of the CDA system used was specified at 112 Wh/ Nm^3. This includes the energy consumed by the compressors and their respective chillers, and the regeneration heaters. On average, operating the Dry Box for 24 hours consumed 23.35 kWh of electrical energy per day.

5.2. Comparison of Results

Table 2 shows all the results obtained from the experiments, including the maximum and average RH values to demonstrate the impact of opening the door of the Dry Box to the Clean Room environment. Additionally, the energy consumption in kWh/day is listed to facilitate comparison across all tests. Figure 6 complements the findings by presenting a graph depicting the relationship between energy consumption for each test.

Table 2: Tabulated the results obtained during the various experiments.

Test No	Seal	Volume Reduction	Open/Close	Dryer	RH - max (%)	RH - average (%)	Energy Consumption (kWh/day)
1	No	No	No	CDA	10.7	7.7	3.34
2	No	No	Yes	CDA	39.1	10.4	23.35
3	No	Yes	No	CDA	10.0	8.0	3.42
4	No	Yes	Yes	CDA	40.6	10.5	22.22
5	Yes	No	No	CDA	10.0	7.3	1.71
6	Yes	No	Yes	CDA	37.0	9.7	20.64
7	Yes	Yes	No	CDA	9.7	7.0	1.87
8	Yes	Yes	Yes	CDA	40.6	9.6	17.18
9	Yes	Yes	Yes	Desiccant Rotor	33.2	11.3	17.75

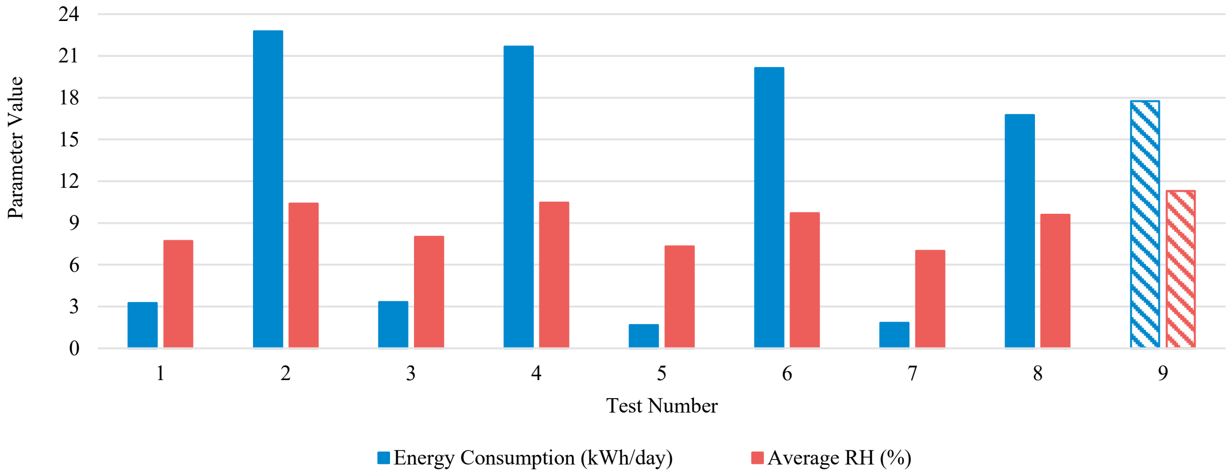

Figure 6: Energy Consumption and average RH for all the tests. The solid-coloured columns represent Scenarios (1-8) supplied with CDA, while the hatched coloured columns show Scenario (9) when the desiccant rotor dryer was used

As expected, the tests with sliding door opening/closing cycles resulted in high CDA and energy demands. As an example, opening/closing cycles of the Dry Box without any improvements (Test 2 vs Test 1), resulted in a sevenfold higher consumption. From the results obtained, one can conclude that using internal volume reduction techniques (Test 4 vs Test 2) reduced the CDA and energy consumption by 5%. When the Dry Box was sealed without using internal volume reduction measures (Test 6 vs Test 2), the demand decreased by 12%. When both improvements were implemented (Test 8 vs Test2), an overall reduction of 26% in electrical energy consumption would be achieved if the volume inside the Dry Box were to be replaced by closed plastic containers filling in the internal, unutilised space and if the sealing were to be improved.

The results of Scenario 9 which used the desiccant rotor instead of CDA to dehumidify the Dry Box, showed that even with the Dry Box alterations in place (Test 9 vs Test 8), the energy consumption increased by 3%. This is based on the assumption that a CDA system has a 25% loss due to leakages. In such case, desiccant rotor dryers will be beneficial for CDA systems with leakages higher than 27.5%. In the case where CDA systems are monitored and regularly maintained, hence keeping air leakage rates low, the hypothesis that a localised dryer would consume less energy than a CDA system is rejected. Moreover, it is noted that the average RH when using the desiccant rotor is the highest amongst the other scenarios, showing that even with a higher energy consumption, the drying capabilities were not improved.

For a factory running 24 hours a day, all year long and taking into consideration the scenario of a Dry Box without any improvements (Scenario 2), one Dry Box would consume 8,523 kWh/annum to operate. By applying the proposed improvements (Scenario 8), one Dry Box would consume 6,271 kWh, therefore saving 2,252 kWh per year per Dry Box. Table 3 sums up the energy savings with respect to electrical energy and the associated reduction in CO_2 emissions if both improvements were to be implemented. At the time of writing, the cost of electricity for businesses in Malta was at € 0.12/kWh [26]. In the last two years, the average reported carbon footprint of the energy mix in Malta was at 400 g CO_2 /kWh [27].

Table 3: Comparison of costs with and without improvements for one year.

Parameter	Without Improvements	With Improvements	Savings
Electrical Energy Consumption (kWh/a)	8,523	6,271	2,252
Operating Costs (€/a)	1,023	752	270
Carbon Footprint (kgCO_2/a)	3,409	2,508	901

Table 4 shows the payback period if both proposed improvements were to be implemented. The seal improvement was implemented by applying aluminium tape, which costs € 5.00 to seal all the joints of the Dry Box, while the plastic containers required to occupy the unutilized internal space cost € 5.50. This implies that these simple improvements require a very low investment which pay back in a very short period of time, while resulting in immediate and significant (26%) energy and carbon footprint reductions. Being highly energy intensive, CDA systems can significantly impact the operational expenses of a semiconductor company, especially when multiple Dry Boxes are used between each process step. Therefore, energy consumption and related costs can be very high. This study shows how these can easily be reduced by 26% if the relatively simple improvements assessed above are applied.

Table 4: Payback period of proposed improvements

Yearly Savings per Dry Box (€/a)	270
Improvement expenses per Dry Box (€)	10.50
Payback period (days)	14

6. Conclusion

The objective of this study was to address moisture-related challenges in the semiconductor industry and to explore simple but effective methods to mitigate these issues while minimizing electrical energy consumption. This involved enhancing existing storage systems and testing an alternative technology to create a dry semiconductor storage environment on a production line. The results conclude that simple improvements such as sealing and reducing unoccupied volume of Dry Boxes were successful, resulting in a reduction in electrical energy consumption and carbon footprint of 26%. A more complex and expensive intervention using a localised desiccant rotor to dehumidify the Dry Boxes proved not to be beneficial. This study shows that implementing straightforward and practical modifications can lead to significant energy savings and decarbonisation, contributing towards a smarter and more sustainable manufacturing industry.

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