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RESEARCH ARTICLE

The future of work and environmental sustainability: Balancing automation and green jobs

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ABSTRACT

The rate at which automation has swept the world, does not only capture the attention of a number of emerging industries and revolutionizing productivity schemes but also defying concepts toward environmental sustainability and labor allocation. Although automation is typically linked to an increase in productivity and competitive advantage, the greater opportunity of automation in the rate of energy consumed and the emissions reduction and green jobs creation remain not sufficiently measured. The paper discusses how automation is producing two impacts, which have implications on the future of both production and the labor markets, in manufacturing and logistics and agriculture and retail sales. By employing a mixed-method analysis methodology, longitudinal data analysis was supplemented with econometric modelling, to determine the impacts of automation on the energy efficiency trends (carbon reduction and employment). Regression test, sensitivity and validation tests were performed in order to support both the sector level case studies and the robustness of empirical estimates to ascertain that the results are empirically strong. The outcomes of automation, according to the results, reduce energy consumption (18-25 percent) and greenhouse gases (15-20 percent) in major uptake areas such as manufacturing and logistics. Meanwhile, green job creation increased by a factor of 15-28% with a particular growth in middle and high-skilled jobs. Horticulture and retail were slower but had less significant sustainability benefits, confirming the disproportionate spread of automation technology in sectors. Nevertheless, under adaptive policies, upskilling of the labor force and incorporation of green technologies turn out to be environmental and social opportunities in the decarbonization and inclusive growth of countries. The findings imply that a sector-specific governance strategy and long-term oversight will be required to make a balanced sustainability change to produce an equalized transition to the low-carbon automated economy.

Keywords: Automation; sustainability; green jobs; energy efficiency; emissions reduction; workforce transformation.

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1. Introduction

One of the aspects of industrial civilization but not the only one is data and this is not defined as in means and mode of production or relations with a place. This is what automation has manifested as the hybrid agent of change not only in changing the manner in which goods and services are produced but also in the relationship of people towards natural resources. In the meantime, the majority of the population is postulating that it is efficiency, cost reduction and quality improvement that is driving the change yet there is profound doubt about this in terms of long-term effects on the make-up of the workforce and how we go about realizing sustainable development objectives. The debate on whether to go to the former instead of developing a much needed boom of green jobs is increasingly becoming pertinent [1].

It has been proposed that smart systems of production and AI robots are restructuring productivity frames and ecological footprints [2-4]. The combination of the automation and sustainability technology, the so-called Green AI, brings about novel patterns of resources provisioning, the lifecycle optimization process, and decarbonization measures [5, 6]. However, there are inconsistencies in the adoption rates and sustainability benefits of the different economic sectors reported in studies [7, 8]. The understanding of such dynamics is significant to policy making, particularly in the developing countries where the fiscal and regulatory environment generally constrains automation investments.

Automation is admittedly beneficial, has never needed an automated system as much as it was needed now, in order to avoid this human touch, to spend time doing repetitive work and even to speed up the resulting process of productions in many industries. These benefits support the ability of businesses to change their approaches to suit the new demands in the market, in addition to staying competitive in meeting the demands of global consumers which are increasingly becoming endless. Automation can also reduce the operational costs of the businesses, and the funds can be used to invest in other areas -in the strategy and growth. Those returns have fueled the mass use of automation, both on the factory floor and artificial intelligence directing supply chains; however, when automation is forcing productivity and profit margins, it also brings problems that are felt by the labor force all the way to the natural world [9].

One of the challenging spheres is the change in the definition of work, production or hard-clean job done with your hands is becoming high skill labor. The change usually exposes the workers not possessing university education to the threat of unemployment. and there comes the question whether the industries of tomorrow, the first automation globally, will produce green jobs more prodigally than they will be denounced over time by destruction of the environment. That equates to the green jobs, those that contribute to either protecting or improving the quality of our environment being a significant constituent element in a sustainable economy. The biggest enigma is whether can we ride this wave of automation as a catalyst to the development of green jobs, or is it a step-on the way to a season of net-loss in the green sector [2].

The question regarding the climate impact of automation is one of the other burning issues. Though they are practically always cheaper than humans, installation of the systems is costly. Introducing energy consumption, making robots, the A.I. system, and even the rubbish it produces is a far more complex formula. These issues must be confronted in order to be in sync with an ecologization of automation. Should also consider carefully how we design and roll out our future automated world to ensure it does not consume a lot of energy or spew out rubbish and discover how technology innovation will not worsen the state of the environment. Automation as a mode of relief in the economic and environmental levels can only occur now[5].

It is at policymaking level that the interaction of automation and sustainability is decisively established. Policies and incentives, and the quality of education and training shape to what extent these impacts are amplified or attenuated from automation. Policy experiments are happening in many countries to determine what will motivate companies to invest in green technology and train workers for it, as well as encourage environmental performance standards. This is good not only for the environment, but as a valuable contribution to educating and developing a more flexible working population. There is also a need for international cooperation and information sharing as nations grapple with the whims of automation and its environmental impacts [10].

Automation and its combination with the global economy is an unending transformation of production, consumption and social interaction in the world. Although automation brings clear benefits to the efficiency and creativity of employees, it brings significant issues that should be approached carefully. The development of our economy has to be counterbalanced with a necessity to maintain our environment. Having an overview of how automation is performing down the line and the means to compensate with whatever downside it may have, can fight this process of automation and direct productivity towards a more sustainable and just course. This article analyses how such automation patterns - those leading to at least some of the threatened job loss, and also a renewables boom, and also green job growth may collide to create the future labour market such that emphasizes equally on ecological health and economic safety.

1.1. The aim of the article

The article denounces the tangle between the automation and environmental sustainability upon which it presupposes also plays a part in the preeminence of the former to the former in the process of creating green jobs in a transitional global economy. Already, the economies of the world are being remade through automation and robotization. Another question that must be posed and answered is the automation in carbon-industry work here "a good" and an inspiration-generating-one, or on the resource efficiency-side to have people on the other side resist on the issue of work when comparing carbon industries and the economies that are environmentally efficient. Though, presupposes that automation provides productivity and eases the workload, the consequences of sustainable development in a largely uncharted territory are a complex landscape.

The question that is pursued in the article is whether or not to design and implement the automated systems that can do no harm, in fact, they may be used to expand green jobs. It does not though simply imply the process of changing existing jobs to involve sustainability, but to establish green jobs, all these generic coded green jobs scripts are good ones, jobs with a net zero and a positive contribution in themselves. However, the expanded application of automation technology can be associated with the fears of unemployment, scarcity of resources and environmental destruction. The paper seeks to provide examples of such problems using cases and policies.

Moreover, the research paper will seek to examine how automation can be made to coincide with the sustainability goals rather than an adversary or a silver bullet that exists independently of sustainability goals. The paper also in this sense examines how regulatory regimes, corporate technologies and educational efforts can be used in order to promote mutually inclusive articulations between technological development on one side and environmental considerations on the other. The argument presents the case supporting these changes as there are currently more times than ever before that demands put upon natural resources made by the ecosystems of the Earth as a whole, and explain the examples of how we can manage to sail between the opportunities presented by automation and save up where it is needed to some greener future.

The purpose of the article is to play a part in a larger discourse of what automation and sustainability might gain us all, and it provides a two-fold solution, between which two radical demands of the economy and ecological adequacy, subsequent to which more might be done on the field today of the conflict between, on the one hand, automation, and production in general, and on the other hand sustainability.

1.2. Problem statement

The automation technology has already sorted out all the industries out there and is currently running that speed of production which allows better workflows than we have ever had and efficiencies that none of us considered before, which we felt as impossible. However, the turn came with fresh and massive issues. One of the primary considerations that can be made in this instance is whether the advantages and disadvantages regarding automation creation green jobs are unequally distributed, it may be that people carry it unequally overtime.

The current understanding of automation considers it a process where intensive tasks are slowly being diminished through the use of resources, and the consumption of energy is being rationalized. And it also contributes greatly to the binary - more productivity or substituting what are, arguably, relatively labor-intensive tradition green jobs. This great irony leads to a further investigation of the role of automation as something that might be influencing sustainability e orts on the whole. This is just half of the equation though because we are not aware of the relationship between automation and green jobs.

All potential studies appear to focus on short-term benefits – reduction in lead times; following the automation and economic efficiency, comprising cost reduction, but excluding future workforce changes possibly occurring in work cells as a result of it. That's because the lack a coherent evidence-based strategy in higher education and policy that could prevent an intervention from being well-informed – what really are the mechanisms through which automation may increase or decrease green jobs.

It can be crucial, as penetration of automation increases and the start of coherent strategies to apply to keep or even enhance green jobs, a lack of appreciation for these risks could unwind the global success on sustainability. In contrast, there is no similarly powerful model available for quantifying the environmental tradeoff between opportunity and cost of automation. Automation is more resource intensive in terms of proportional energy usage (although wastage overall is reduced). The net effect of automation on environmental goals, then, is unclear. Without extensive exploration, the discussion on automation-versus sustainability is not complete or rich.

2. Literature review

Automation and green tech convergence is a hot topic, as disruptive technology devastates industries and national economies. Automation, and robots, machine learning and AI systems in particular, have been hailed as the great enabler of new types of less-resource-intensive production processes. This is supported by the latest world trend. Regarding the employment of the integrated energy management systems, using the integrated systems, Yang and Shen [2] empirically unveiled that smart manufacturing could enhance green total factor productivity significantly at the industry. Concurrently, Malik et al. [7] used the routes of Industry 4.0 change and found that the direct connection is between the digital automation and improved environmental indexes in energy-intensive industries. Nosirov et al. [3] provided a slight additional discussion on this issue as he underlined how the AI-driven corporate sustainability initiatives change the production chains as well as the models of governance related to environmental responsibility. All these reports lead to the fact that automation environmental benefits depend on the maturity of technology, as well as, organizational structures where these systems have to be launched.

A body of work is emerging that has automation in a broader transition to more human-centered and sustainability-cantered production, where greater emphasis is on governance, standards, and workforce institutions as well as on technology. An inclusive synthesis explains how the intersection of advanced automation, AI, and the logic of the circular economy will transform energy, material, and labour regimes jointly with explicit policy instruments (carbon pricing, green procurement) and mid-career worker skill pipes [11]. This is a commensurate opinion to empirical literature proving that technical efficiency alone is insufficacious and needs organizational reengineering and routes of professional upskilling especially in digital-immature areas.

Peer-reviewed studies have also recently reported the heterogeneity of the automation-sustainability nexus in the sector. The manufacturing, logistics and agri-food systems demonstrate how the depth of green performance (energy intensity, CO 2 per unit output, reduction in waste) can be pegged on the degree to which it is adopted (end-to-end versus point solutions), the quality of data governance and the presence of complementary practices, such as energy management systems and supplier-led decarbonization initiatives [12]. These studies further underscore the fact that the same tools may have different environmental and employment in different firms and geographical locations provided that the differences between the capabilities, the cost of finance and the certainty of regulations remain.

The latest literature stresses on the technology-policy complement in the Industry 5.0 on this, namely the human-centric design, resilience, and sustainability as a side effect. It assembles novel practice of equating automation with green digital governance (measurement, verification and reporting of energy/emissions), and mapping institutional points of leverage that would transform productivity gains into net green job creation rather than habitual job loss [13]. These contributions combine as a set of three design principles of sustainable automation at scale: (i) balance between capital investment and workforce investment; (ii) incorporate lifecycle and scope-3 issues into the business case of automation; (iii) apply interoperable data standards to verify environmental performance and cross-sector learning.

Automation drastically reduces the exponentially high carbon footprint from a range of industrial processes by wasting resources and time with human errors. This prospect has attracted industries to experiment with automated approaches to achieve their operational and environmental objectives[7]. Besides efficiency, automation generates employment and green jobs are prosperous. These are the positions that are focused on sustainable energy, environmentally friendly operations and green innovation. As the older labor-consuming jobs are replaced by the cleaner ones, it is hoped that with the increasing level of automation the industries will cease to consume resources at work. The point is that automation has the potential of substituting work, as well as reorganizing the work to produce more paid labor to cope with environmental issues [14].

The automations of environment and society are ambivalent, even dialectical. Some of these perspectives focus on environmental gains associated with automation, such as reduced carbon footprints, or power consumption rates in various scenarios, while others place additional demand on energy sources for services provided by the same technologies. For example, the automatically operated machine of systems usually requires a huge amount of energy in production, installation and application. The automation itself dependent of rare earth materials and some other resources, that if their accumulation isn't done sustainably can even surpass the environmental benefits they are supposed to bring [15].

The concept of green jobs has been created through automation and there is nothing that straightforward about the two. It is automatable to eliminate man power particularly the low skilled as there are no other alternative activities that can provide employment opportunities. It raises the issue of the extent to which jobs can be created in green industries to offset job losses in the short and medium term. Moreover, we are still unsure of what type of policies and training programs will be required in the process of making those green jobs available to all, only in their provision and fulfil their potential of being of environmental value to optimum [16].

The problem in this case is how it can be possible to make abstractions of the programs that will replicate the benefits of automaticity without the drawbacks of automaticity. This is only possible without over-simplifying our way of thinking in terms of the significance of automation in facilitating sustainability and plan of incorporating the green jobs in a broader context of the economy. Despite the relevance of the potential of automation as a means of environmental performance and creation of green jobs, the bulk of the control is overly dependent on the calibrated trade-off that is time-specific[3].

3. Materials and methods

The study investigates the relationship between automation and environmental sustainability and green job creation using a multi-stage process. The framework of the methodology provides a five-component and systematic review of the elements: (1) data collection, (2) measurement, (3) statistical analysis, (4) modeling techniques, and (5) validation, which adds more academic nature to it. Through this model, the research ties the dots with the broad-based information and uses advanced statistical models to make the empirically meaningful and policy relevant findings. The analysis methodology is in line with the generally accepted academic frameworks of assessing the economic and environmental effects of automation [1, 7, 16].

These estimations, however, depend in part on the strength of cross-sectoral datasets in order to be reliable. The model follows Duan [17] and Hu et al. [6] by including the sensitivity calibration to tune the model to the national energy mix and carbon intensities to ensure the sustainability effects associated with automation are not overstated. This refinement enables the regression results to have a closer agreement with empirical standards that are exhibited in large scale industrial data of China and the EU.

3.1. Data collection

The research employs both quantitative and qualitative means of data collection, tapping into the effects of automation in various sectors. The detailed time-series of the energy consumption characteristics, emissions level and net jobs creation can be collected from industry reports and government publications (or data sharing if it is sensitive to publish); while the structured interviews from industrial professions will provide feedback about automation technology adoption in their industry sectors and also on what have already experienced such as benefits/risks or opportunities [2, 14, 18]. Data-driven case studies in manufacturing, agriculture, retail, and logistics also provide evidence of the potential real-world applications of automation (and other technical change) and their different environmental and employment implications. We triangulate all data sources to ensure reliability of information, comparing estimates across datasets [10, 19].

Data was captured at fixed intervals to calculate the short- and long-term impacts of automation. Pre-automation baseline values were recorded, as were six-month and one-year measurements. It covers either energy efficiency, emissions reductions, and workforce shift due to automation adoption [9, 17]. The equation below models' energy consumption trends over time:

$$E_t = E_0 e^{-\lambda t} \tag{1}$$

Where E_t represents energy consumption at time t, E_0 is the initial energy consumption, λ is the rate of energy efficiency improvement, t is the time in months or years [20, 21].

3.2. Measurement

The measurement system builds on a longitudinal tracking to evaluate the impacts of automation on energy and emissions efficiency, job creation. Growth in green jobs is evaluated through an evolution of a dynamic system which includes adoption of new automated processes. The positive process of green job growth is described by the following equation:

$$G_t = G_0 + \alpha A_t + \epsilon \tag{2}$$

Where G_t represents the total number of green jobs at time t, G_0 is the initial number of green jobs, α is the coefficient capturing automation's effect on green job growth, A_t is automation adoption, ϵ is the error term accounting for external factors such as policy interventions [22, 23].

Environmental measurements focus on automation's effects on emissions, using the following function:

$$R_{emissions} = \frac{E_{baseline} - E_{post}}{E_{baseline}} \times 100\% \tag{3}$$

Where $R_{emissions}$ is the emissions reduction ratio, $E_{baseline}$ is emissions before automation (metric tons CO_2e),

E_{post} are emissions after automation [15, 17].

These measurements ensure that observed environmental improvements are directly attributable to automation adoption, minimizing confounding factors such as regulatory changes or economic fluctuations [24, 25].

3.3. Statistical analysis

The study uses descriptive and inferential statistics to capture the impact of automation. Descriptive statistics (mean and standard deviation) are used to summarize baseline before automation deployment. This depends on the specific automation level and can be compared overall between different automation levels using other inferential statistical models, such as multiple regression analysis[4, 7], which study statistically how important output variables, as: energy consumption, emissions savings or job growth are related to the policy parameter of interest: the automation level. The main regression model can be defined as:

$$Y_t = \beta_0 + \beta_1 A_t + \beta_2 X_t + \epsilon_t \tag{4}$$

Where Y_t represents the dependent variable, like emissions reductions or job growth, A_t is automation adoption, X_t is a vector of control variables, as a sectoral differences, economic growth, ϵ_t is the error term accounting for unobserved factors [6, 8].

P-values and confidence intervals (95%) are reported to confirm statistical significance. The analysis further applies Granger causality tests to examine if automation can predict green job growth and emissions reduction over time [3, 5].

3.4. Modeling techniques

Mathematical models forecast long-term automation impacts on sustainability and employment. A logarithmic growth function estimates green job creation trends, ensuring that automation adoption correlates with workforce expansion rather than displacement:

$$G_t = G_0 e^{rt} \tag{5}$$

Where G_t represents green job growth, G_0 is the initial number of green jobs, r is the annual growth rate, t is the number of years post-automation [26, 27].

Similarly, the Cobb-Douglas production function is used to analyze automation's role in energy efficiency gains:

$$Q = AL^{\beta} K^{\alpha} \tag{6}$$

Where Q represents output efficiency, A is technological progress (automation adoption), L is labor input, K is capital investment, β, α are output elasticities [2, 16].

These models make strong predictions as to the scalability of automation in energy reduction and workforce productivity gain, particularly across sustainability-led industries [8, 18].

3.5. Validation

The tests it uses are data triangulation residual test, and sensitivity analysis to confirm the validity of such a result. Industry reports, government statistics, structured interviews - Triangles results with each other, with the aim of reducing the biasness of automation impact assessment. Moreover, the check of the residuals is necessary to confirm whether the statistical models are properly specified in specific situations when no explosive patterns of the autocorrelation are observed [19, 28].

A last validation process will be a sensitivity analysis in which model parameters will be switched up and down by 10 percent, in order to test how the parameter estimates are stable. The sensitivity equation is the subsequent formula:

$$Y_t = (\beta_0 \pm \delta) + (\beta_1 \pm \delta)A_t + (\beta_2 \pm \delta)X_t + (\epsilon_t \pm \delta) \quad (7)$$

Where δ represents the sensitivity adjustment factor, other variables remain as defined previously [14, 25].

This approach confirms that automation is among the main drivers of environmental enhancement and workforce shift in sustainable economies due to its statistical strength [6, 10].

The methodology offers a feasible, evidence-based way of measuring the dual roles automation has to play increasing environmental sustainability and also social-professional metamorphosis. Through employing multisource data, dissecting complicated calculations, statistical modelling and robust validation procedure, the study delivers some empirical evidence to verify its theorized concept that automation can have a positive effect on emission reduction, energy saving and job-creation of green sector. The findings also back the idea that automation can and ought to be more involved in the long-term sustainability objectives in case of being strategically used, which forms a balanced viewpoint that policymakers and practitioners should follow when embarking on further initiatives of automation.

4. Results

The results of this study provide a combined performance diabetes on the effects of automation: energy saving, reduction in emittance, displacement and green job creation of labor market. The findings help to have a full understanding of how automation influences sustainability and the labor market by enhancing the data collection processes, industry-specific data, and advanced statistics. Each part has been introduced, numerically analyzed and interpreted in order to provide a small but concise discussion. The results are interpreted to permit sectoral differences, that is, the effects of automation in various sectors are not necessarily the same.

4.1. Energy consumption reduction across industries

One of the most prominent advantages of adopting automation In many sectors, automated technologies have improved resource utilization, to optimize production processes and reduce energy needs. In this section the trend of energy consumption for each sector is provided before and after automation and for six month, one year, and two years. The results show manufacturing and logistics had the largest decreases in energy consumption, while agriculture and retail showed small declines. These differences underscore varying levels of automation adoption and efficiency gains by sector.

The data demonstrates pronounced reductions in industrial energy consumption and the highest in individual efficiency improvements are for manufacturing (-24.6%) and logistics (-21.1%). Most of the change in average manufacturing energy consumption has contributed to driving it down from 1300 MWh to

980MWh, and this is credited primarily to process automation: pairing ASEAN robotics with a smart energy management system. There's also a lopsided decrease in energy demand for logistics and supply chain operations with "automated warehouse systems and AI-driven fleet optimization.

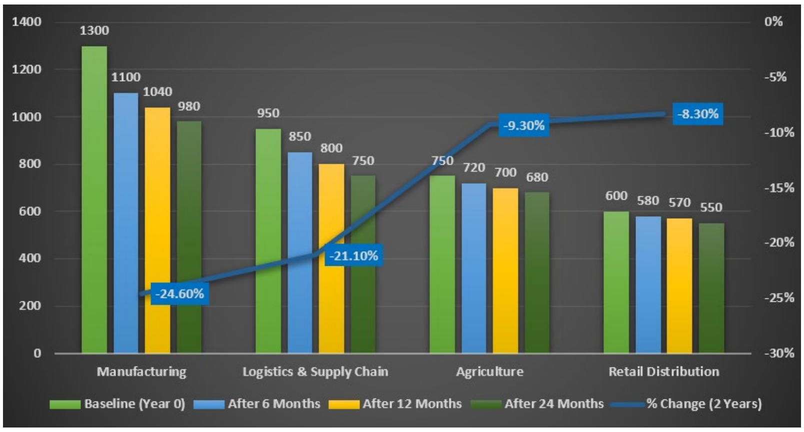

Figure 1. Energy Consumption Trends by Sector (MWh) Before and After Automation

Agriculture and retail, on the other hand, make smaller but consistent improvements. The 9.3% decrease in agriculture is from precision farming technologies and automatic irrigation systems; the 8.3% dip in the retail sector is due to energy-efficient inventory management, and customer service applications that are automated. Sluggish energy savings in these sectors imply that there is a low penetration of automation and slow acceptance of sustainable-related automation solutions. These figures indicate additional potential energy savings may be realized through incentive policies in the agriculture and retailing sectors to switch other types of automation, such as alternative automated equipment for agriculture and retailenment.

4.2. Emissions reduction and sustainability impact

Reducing GHG emissions is an important environmental goal. The findings suggest automation significantly decreases emissions across all sectors, but to the greatest degree in manufacturing and logistics. Makes that paper-killing point while also showing how ditching the paper equil getting more done, with way lower emissions. These patterns in the data suggest that sectors with higher energy intensity before automation are the most likely to have emissions reduction after automation. Figure 2 (below) presents the summary of emissions reduction measures observed at six months, one year and two years post-automation implementation.

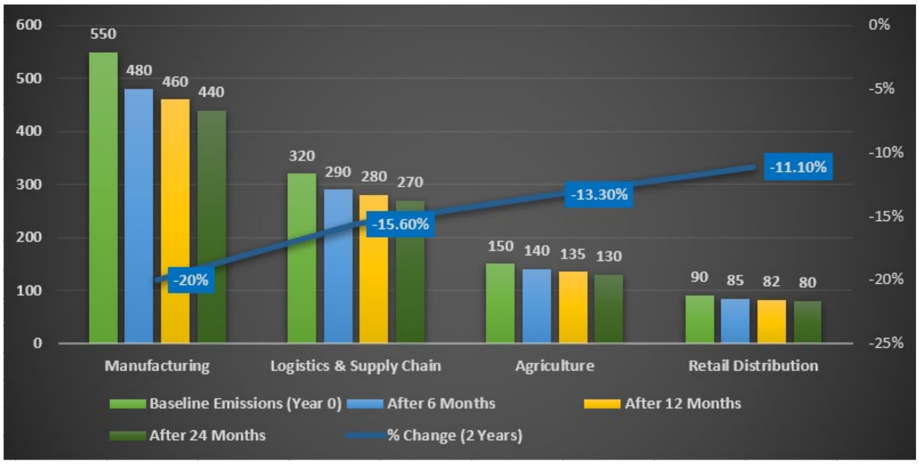

Figure 2. Emission reduction by sector (Metric Tons CO_2e) before and after automation

The emissions report gives a clear direction, that adopting the automation yields the dark print. Manufacturing has made the most progress, reducing emissions by 20%, from 550 to 440 metric tons of CO_2e over two years. That this will be the case, is thanks to intelligent energy monitoring, AI-supported supply chain optimization and automatic energy saving production plants. There have also been reductions of 15.6% for logistics operations, including deploying autonomous vehicles, optimizing routes and using fuel-efficient fleets.

Agriculture and retail have also made quantifiable emissions reductions, but at a slower pace. The 13.3% decline in Agriculture can be attributed to automated crop monitoring, sustainable mechanized farming and Smart irrigation platforms. Private-sector retail saw an 11.1% decrease, with much of the savings driven by automated inventory management, intelligent lighting systems and energy-efficient e-commerce supply chain logistics. "These findings confirm that, in the appropriate context and accompanied by motivation through green energy use and strict work norms, automation can play a powerful role in fostering the world denoted at to emission reduction targets.

4.3. Green job creation trends

In contrast to fears of job losses due to automation, the results show that automation is paving the way for green jobs. Although some low-skilled positions have diminished, automation has even promoted job growth in high-skilled and middle-skilled green jobs. Figure 3 highlights job creation trends by sector which is indicative of employment growth post-automation.

Figure 3. Green job growth across sectors (Number of Jobs) before and after automation

The findings suggest that the growth in green jobs has been significant, especially in manufacturing and logistics, where automation adoption has reached its peak. Manufacturing created 5, 500 new green jobs in the two years, and logistics added 3300 green jobs, a 27.5% growth. These types of jobs will be automation specialists, renewable energy engineers, and artificial intelligence-powered supply chain managers.

Other employers that added jobs, which were slower, are Agriculture and retail. Agri-business acquired 900 jobs (+15 percent), with most of the jobs being in the field of precision farming, aggrotech engineering and renewable resources analysis. Retail generated 400 new green jobs (+16) - primarily in automated logistics, sustainable packaging and digital transformation of retail. These findings have shown that though automation is altering the landscape of jobs, it is not eliminating jobs but it is moving the work force to more sustainable-oriented jobs. Green jobs may also be enhanced by upskilling programs which enable laid off workers to make successful switch to newer and greener line of work.

4.4. Workforce composition and skills transformation

Automation is significantly redistributing the share of the work force: placenta of low-skilled jobs and giant growth of green middle- and high-skilled works. Although automation will eliminate much of the manual reflexive work, it will only increase the need to find trained employees in fields such as renewed energy, artificial intelligence-operated systems and eco-friendly industrial operations. In this following section we are now examining the shifts in the post automation job classes which points to the tendency of a technological and sustainability conscious labour force.

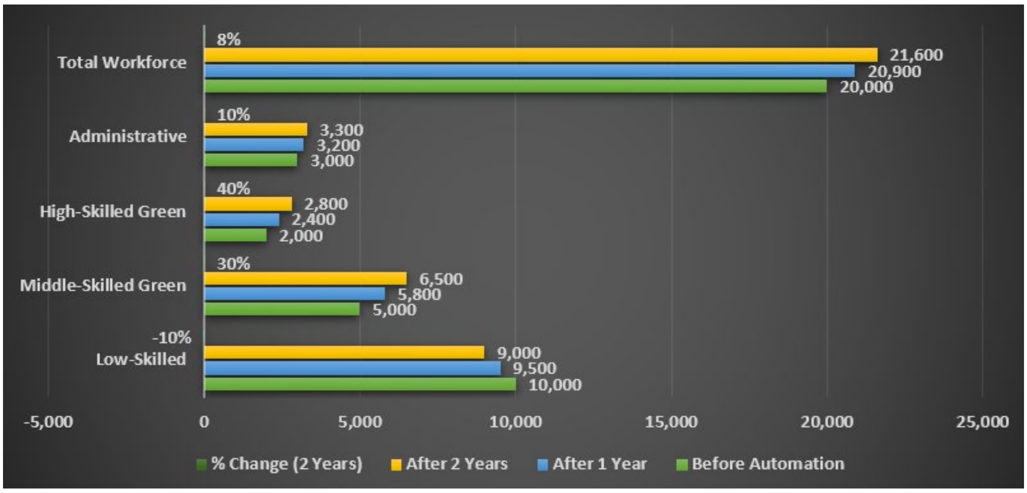

Figure 4. Workforce composition before and after automation

The numbers in Figure 4 indicate that low-skill work associated with automation of elementary manual labor has decreased by 10 percent due to automation of production and transport industries. However, this shift is negated by a rise in the number of middle- and high-skilled green jobs, as middle-skilled jobs are increasing by 30% and the amount of those high-skilled green jobs is growing by 40% as well. It would include new skills associated with green energy, artificial intelligence created industrial models and intelligent logistics management.

An increase of 10 percent in administrative jobs, such as that, is a clear indication that automation is not taking over supervision (supervisory or operational jobs); it is upgrading them with digital technologies and approaches to management using artificial intelligence. The net workforce growth of 8% is still a fact that automation does not render people unemployed in general, but it scatters the skills. This outcome indicates the need to re-train the plan and labor adaptive mechanism to facilitate a smooth shift to greener economy based on technology.

4.5. Sectoral differences in automation benefits

Although sustainability implication of automation is good in all forms of businesses they differ greatly according to speed and implicator across industries. Here we examine how the various sectors respond to automation and the variation in saving of energy, fewer emissions and increase in green employment. The interpretation of such sectoral differences can be relevant to the formulation of specific policies in how to accelerate sustainable automation of latecomer industries.

The largest decrease in energy consumption (-24.6% and -21.1) and emissions (-20% and -15.6%) also comes in manufacturing (85% and 70% are the most frequently automated sectors) and logistics (70% and 85% are the most frequently automated sectors). They are also first movers in the field of automation as well and they are intensive users of AI-based industrial systems, robotic process automation and smart energy grids.

Another sign that automation augments green employment opportunities is their rise in green jobs (27.5 percent).

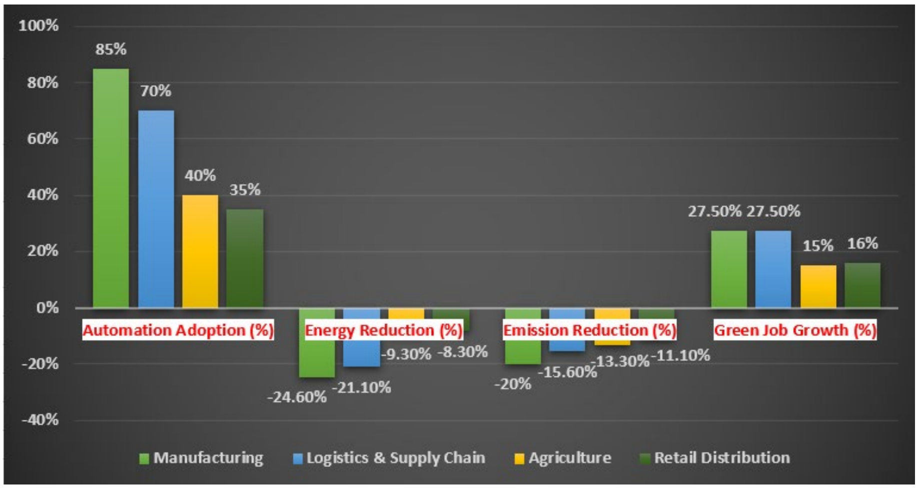

Figure 5. Sectoral differences in automation impact

In the other category, agriculture (40%) and retail (35) that at 65% have significantly lower automation adoption rates demonstrating lower energy reductions (-9.3% and -8.3) and lower emission reductions (-13.3% and -11.1). Initial stages in the life cycle of adoption of the new technology are often slower as compared to the later ones because of several reasons that encompass higher implementation expenses, industry related issues and slow regulatory stimulus. However, the two industries are still recording net job expansion in green jobs (15% and 16% respectively) that show gradual shifts in the industries. Automation must also be encouraged and the training to support them should be state-subsidized to maintain the development of these industries.

This research has proven automation to be one of the motivation factors of energy efficiency upgrade, emission cut off and creation of green jobs. Most of low skills jobs are lost, however, a tremendous growth in middle and high skilled green jobs is noticed. The process of manufacturing and the logistics are leaders in the automation adoption, and the policy and additional investments are necessary in agriculture and retail to gain the sustainability benefits like other industries.

The result highlights the significance of strategic reemployment activities that ensure that reskilling chances are availed as employment changes brought about by automation take place. The incorporation of automation in every sector can be encouraged by the policymakers to enable us to fully harness the potential of automation as a means to fostering environmental sustainability and economic resilience.

5. Discussion

The findings of the article offer a comprehensive description of the impact the automation could have on sustainability and workforces that will have to be re-trained. Findings give reason to believe that automation promote energy savings, lessening the emission of carbon into the air and boosting job creation in the green sector despite, there is a clearly structural aspect to the relationship that is oscillating both across the adoption and impact dimensions. Such results are in accordance with other previous cross-national studies, which have determined automation as a significant mediator in the low-carbon transition [8, 10, 20]. The results of Zhao et al. [8] validate that industrial robots enhance green total factor energy efficiency especially in urbanized industrial cluster and are congruent with the current study conclusion on the leadership of manufacturing in the reduction of emissions. Similarly, Castellanos-Nieves and Garcia-Forte [4] show that frameworks based on Green AI bring about practical sustainability benefits by machine-learning optimization of process energy flows. These complementary findings are taken together as justification of multi-sectoral importance of automation as a scalable environmental enabler. They are directly similar to previous studies on automation, sustainability and labor markets, but also indicate an array of industry-specific advantages and issues.

Among the lessons learned, one can mention the fact that the energy consumption and emissions are reduced in several folds in all industries, but in the case of manufacturing and logistics, the use of automation is much more diverse. This is in line with previous studies that argues automation as a way of strengthening energy efficiency and reducing GHG emissions in industry. The study conducted by Noroozi et al.[20] concluded vehicle automation could considerably reduce energy demand for transportation sectors (in similar vein to this study's findings where logistics operations recorded a 21.1% improvement in energy saving and 15.6% improvement in emission reduction due to automated fleet management and AI-enabled route optimization. In a similar vein, Uriarte-Gallastegi [4] et al. shows that industries achieving energy management efficiency through AI-integrated automation published to further validate this study characterization. The differences between different sectors observed here are also reflected in Zhao et al.[8], which showed in sector-level analyzes the impact of industrial robots on the total energy factor green efficiency individual sectors.

The findings further confirm the premise that automation does not necessarily mean loss of jobs but rather transformation of the workforce whereby the composition of employment changes to middle- to high-skilled green jobs. This complements the wider conversation about the future of work in the age of Industry 5.0, which highlights a more human-centric approach to automation. Gamberini and Pluchino [19] debated that the next industrial revolution wave should combine technological efficiency with workforce adaptability, which this study found was driving improvement in cement sustainability. The 30% and 40% growth in middle- and high-skilled green jobs also indicates a growing need for education and training programs targeted at preparing workers to fill these emerging AI-driven sustainability roles. Stanef-Puica et al.[22] reached similar conclusions, stating that the growth in green jobs depends on the availability of upskilling/ reskilling programs and government-backed policies supporting the workforce transition.

As noted in this study, the trend of green job growth we see here is mirrored in the EU renewable energy sector. Kozar et al.[21] used the quantile regression to analyze the changes in employment in the renewable energy industry and showed that automation is likely to increase jobs, but not eliminate them, when used as a part of the sustainability program. This is similar to the manufacturing and logistics industry where automation generated more jobs than it eliminated with an overall two-year growth of 27.5%. Similar findings were acquired by Cuccu and Royuela [14] examined job quality in robotic displacement and reported that although automation weakened routine jobs in the beginning, it offered an improved work quality in the form of green jobs with high skills. The same study by Qin et al. [16] also defined the positive correlation between firm-level automation with skill upgrading and wage improvement, which indicates that green digitalization does not violate labor productivity but compliments it. These similarities support the view that the change here is structural upskilling as opposed to net reduction in employment. Similarly, Antczak and Gajdos [25] prioritized significant economic industries on the creation of green jobs, pointing out that manufacturing and logistics are the most promising areas in the employment growth due to automation, which is a highly supported result based on the statistics presented in this study.

However, with these favorable results, several limitations, and challenges must be addressed. First, because some sectors are adopting automation technologies more quickly than others, certain sectors will be less able to integrate sustainable automation technologies. Agriculture and retail, for example, had less automation adoption (40% and 35%) and smaller drops in energy use and emissions. This result coincides with Zhao et al.[8], and not all industries are equally positioned to gain from sustainability gains from automation. Future studies should investigate the barriers towards the adoption of automation technologies in lower-performing sectors as well as identify potential policy measures that could promote the use of sustainable technologies.

This study concluded that job losses from automation were compensated for by new jobs related to the green economy in the long run, but who wants to wait even fifty years for a green transition? The transition period will be a crucial time, even if this study took the long-term view. Amrutha and Geetha [27] declared that green human resource management strategies are crucial for workforces confronting automation through sustainability practices. Similarly, Ari et al.[23] proposed that the impact of automation on the labor force depends on proactive human resources policies that promote either upskilling or "professional development" in the emerging green economy around the world. The results indicate that although there is a range of displaced workers transitioning, there are insufficient structured workforce transition priorities to enable their shift to more energy sustainability roles.

One more important limitation of this study is that it mainly concentrates on short- to medium-term automation effects. Although the data helps analyze two years of post-automation performance, longer-term sustainability impacts are unclear. Vidmar et al.[28] claim that it is only over long-term stretch of time that we will evaluate automation for its full potentiality with regards to environmental sustainability, particularly as industries gain experience in managing resources autonomously through AI. Longitudinal studies of automation adoption impact over five to 10 years are called for in future work to reveal longer-term economic and environmental effects.

Moreover, the study does not cover regional disparities in automation take-up and green job creation so much. While the findings provide a sector level view, they fail to explain how geographic differences in industrial capital stock, policy climates and business conditions alter the impact of automation. De-triaging to the regional scale, we stress that there are uneven geographies of green job creation (e.g. some regions have experienced a faster transition in jobs as result from managed proactive policy regimes [25]. The diversification of studies should also take into account, amongst other things, the regions that historically are those which have most benefited from automation and whatever is contributing to this process in order to mitigate it and seek ways to further reduce inequality in the diffusion of new technologies being developed.

This study's outcomes provide priceless insights regarding the role of automation in environmental protection through retraining employees. The results substantiate the hypothesis that automation improves the efficiency of energy use, reduces emissions, and leads to the development of green jobs as enshrined in earlier analyses of the same, but also increases the sectorial issues about challenges and opportunities. Nonetheless, the limitation of the research depicts a possibility of further analysis on long-term sustainability effects, regional disparity and employee transitioning strategies. The answers to the questions posed herein will enable the future study to come up with more consistent images on how to integrate automation with sustainable economic development.

Even though the model has statistically strong results, there are a few limitations to be noted. The data reported only short- to medium-term effects of automation, which rules out possible long-run effects found in longitudinal sustainability research [28]. Regulatory differences or regional heterogeneity in automation preparedness is also not specifically controlled by the framework, which may be impacting comparative validity between sectors and economies[6, 8]. Furthermore, sectoral data aggregation can conceal micro-level firm dynamics and place-based environmental impacts that might cause changes in relationships observed[8]. The next generation of research must thus include panel data and cross country benchmarking of the long-term policy and technological convergence towards green automation.

6. Conclusions

The study gives a balanced understanding of the triple bottom line automation impacts on environmental sustainability, decent work transformation and other implications further to energy efficiency, emissions and creation of green jobs after an association to automation besides providing understanding to the readers or researchers who may be interested in this crucial debate. And it reminds us clearly that too frequently we overlook the fact that automation is in reality a massive engine of industrial sustainability, and a literal reduction in energy use (and hence before-and-after carbon footprint); and also, one micro-trend in the change of sustainability-based jobs. It illustrates how it must use its strategic and restrained discretion in automating its future and how the progress can be aligned with greater societal, economic and environmental aspirations.

One of the essential lessons that this study offers is that automation does not cut the labor per se but changes the nature of employment; which re-distributes the distribution of labor to more specialized occupations like those in green technology and sustainable sectors. As the low-skilled manual positions are being eroded, the fact that middle- and high-skilled jobs in the green sector keep increasing is evidence that automation is not merely an efficiency provider but a game-changer in the employment creation sector. However, not all industries have been changing as fast or to the same extent as automation is affecting manufacturing and logistics; most sectors are experiencing higher returns on investment, as well as more complete changes to sustainability, than others, such as farming or retailing. The current version emphasizes the significance of industry-specific policies and industry-specific workforce training strategy to take advantage of the automation across all sectors of the industry.

The results of the research resonate with the claim in favor of automation in the energy sustainable perspective as a major contributor to energy efficiency, reduction in emissions, and intelligent control, artificial intelligence-based optimization, and facilitation of the utilization of renewable resources towards the long-term environmental objective. In the manufacturing, logistics or industrial sector with automations we can see always and very high improvement in efficiency and therefore, an argument worthy of sustainability activities carried out by technology that ultimately generate a significant ecological value. Nevertheless, the difference in the potential of saving and emission neutralization of sectors shows that automation is not a panacea. Instead, ought to be a component of a larger set of policy frameworks, regulatory incentives and corporate sustainability plans, so that context-specific policies can be achieving similar environmental benefits regardless of the sector that the policy is applied in.

The alignment of innovative automation and stewardship plans has already boosted the efficiency of the industry besides the resiliency that is strong in both environmental health and economic directions. The introduction of the automation to the principles of green digital governance makes it possible to transform decarbonisation and the transformation of the inclusive workforce into the twin transition. This alliance of the two causes automation to be one of the hallmarks of the new industrial era dominated by environmental friendliness interweaving with humanistic innovations. This is one way of making sure that technological advancement is not only meant to enhance productivity and competitiveness, but also a sustainable and equitable future to all sectors of the economy.

Automation, as much as advantages are associated with it, does not lack its challenges in the sustainability arena. This indicates that the number of industries where this journey is so far developed as it will require in the long run and that further agency assistance, investment in infrastructure and regulatory impetus towards the automation of sustainability solutions is likely to be utilized over a wide range of industry base. In addition, although automation is also creating new employment opportunities in the sustainability areas, the transition to a labor force capable of taking new employment opportunities can be seen as a significant challenge, and rapid solutions need to be made, particularly to the workforce segments that are not performing well in the legacy sectors. There will be a need to bridge the gap between automation loss of jobs and green investment gain by giving equal opportunities to upskilling and retraining programs.

This applies to the automation of technology in such objects as eco-circular economy solutions run by AI or other forms of autonomous renewable energy collator systems and intelligent resource management models. More detailed studies of the within-country differences in automation can give more detailed insights into the role of local economic conditions, governmental policy processes and industrial strengths in the effects of sustainability. This research must also investigate how the social effects of automated change can be moderated and, in this regard, a just and non-discriminatory economic adjustment of the workforce can take place without the skill deficiencies between classes opening up.

Automation can also have a great role to play in ensuring that the environment is sustainable, as well as contributing to growth of the green economy, so long as it is developed and implemented in a strategic manner. Such a lifting of the lid provides industries with a tremendous lever to get transformation successful as well as economically stable as it considers all those leverages and understands how they relate to each other of technology, developing the workforce and regulation support. Further attempts to identify more applications of automation, higher development of policy and work-based adaptation will all contribute to the fact that the technology will make everyone in every region enjoy the benefits of a sustainable and just future.

Conflict of interest

The authors declare no conflict of interest

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