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Sustainable Engineering Practices: Innovations in Green Technology for Future Infrastructure

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Abstract

Environmental issues have been aggravated by the increase in urbanisation and growth of infrastructure globally and therefore the current mode of engineer work needs to be transformed to a more sustainable one. The conventional construction techniques lead to excessive emission of carbon, waste human energy and consume resources indicating the significance of development of new environment-friendly constructional designs and techniques.The research examines the ways of applying green technology, e.g. solar and wind power plants, energy-saving materials and ways of saving water, to infrastructure construction plans. It is concerned about the application of such technologies in the developing world such as Pakistan. An organized case study, performance analysis, and comparison metrics were part of the means in which we saw the environmental and economic impacts of such sustainable methods.The findings indicate that the energy efficiency, cost savings as well as reduced carbon footprints ahave all been positively impacted in most of the case studies. Projects utilizing renewable energy experienced large reductions in the costs of the energy used. Much drinking water was also saved using rainwater harvesting systems. As well, green building materials enhanced thermal performance, i.e., reduced energy consumption and environmental pollution.These findings demonstrate that not only is sustainable engineering a possibility, technically speaking, but also economically wise and cost-saving in the long-term. Although issues exist, such as high start-up cost and opened regulation loopholes, the positive effects of such a switch on a large scale in the long-term perspective, (i.e. improved environmental resilience, less dependence on resources, and higher quality of urban life), are the factors which demonstrate that it is important to do it. According to the report, it is required to have in place a strong national framework alongside legislative support, stakeholder training, and engagement of the populace to ensure that sustainability becomes part of the future of infrastructure development.

Keywords: “Sustainable Engineering”, “Green Technology”, “Infrastructure”, “Energy Efficiency”.

INTRODUCTION

The infrastructure business has gained huge significance in the quest toward more environmentally friendly methods as more individuals all over the globe concentrate on sustainability. Sustainable engineering is an activity that implies the development and construction of infrastructure that produces minimal impact on the environment, as well as enhancing the health of individuals and the economy (Rashid et al., 2021; Khan et al., 2019). This change is occurring due to the increased concern of people with climate change, scarcity of resources and destroying the environment. This implies that we have to abolish the old approaches to construction of infrastructure.Efficient population and industrialization have imposed much pressure on the natural assets resulting in increased energy consumption, pollution, shrinkage of land and water resources (Shah et al., 2018; Ahmed et al., 2020). By adopting strategies such as the employment of new technology, renewable energy systems, energy efficient designs and environment friendly building materials, sustainable engineering practices attempt to reduce these impacts (Ali et al., 2021; Jamil et al., 2019). All these measures aid in reducing the environmental burden of infrastructure works at the same time assisting in attainment of national development objectives.The core of this shift is green technologies, in particular, the utilization of solar, wind, and hydropower in infrastructures and transport infrastructure (Khan et al., 2019; Mehmood et al., 2018). Increasingly, citizens adopt recent concepts such as passive design, high-performance insulation, and smart energy systems in order to consume less energy and enjoy maximum utilization of resources (Ali et al., 2020; Hussain et al., 2020). Moreover, the employment of such materials as bamboo, recycled steel, and low-carbon concrete is quite significant in reducing the carbon intensity of infrastructural development (Shah et al., 2018; Usman et al., 2018). In underdeveloped regions (i.e., Pakistan), the lack of money, the wrong kind of technology, and the wrong kind of rules are the biggest issues about usage of green technologies (Ahmed et al., 2020; Usmani et al., 2021). Nevertheless, a growing trend of supporting sustainable activities provides us with an opportunity to establish a correlation between environmental goals and economic advantages, including reduced energy consumption, improved quality of life, and sustainable infrastructure (Bashir et al., 2020; Zahid et al., 2020).

This article examines the latest green technologies, which are transforming the manner infrastructures are constructed in

Pakistan and elsewhere. Examining the case-studies and issues related to implementation of the ideas, it allows illustrating how sustainable engineering can provide the economy, the environment and society with more stability. It also provides a framework of strategy to overcome the adoption barriers emphasizing legislative support, financial investments, and people (Ali et al., 2020; Ahmed et al., 2021).As the global focus shifts toward sustainability, the infrastructure sector has emerged as a key player in driving the transition toward greener practices. Sustainable engineering encompasses the design and construction of infrastructure with an emphasis on minimizing environmental impacts while simultaneously fostering economic and social well-being.

METHODOLOGY

Solar and wind energy are considered some of the major renewable energy sources, and their integration into the infrastructure plans of various projects is now one of the underlying approaches to limiting the use of fossil fuels and addressing climate change effects. These technologies not only create a clean source of energy but also help in energy independence and in the process of decreasing greenhouse gas emissions.Solar Power Energy: Solar power, commonly created via photovoltaic (PV) cells or concentrated solar power (CSP) systems is a green technology that has gained most popularity in infrastructure developments. Solar panels are attached to the rooftops, facade, and other surfaces of buildings in order to tap solar energy in urban infrastructure and move away the dependence on the traditionally used electricity generated based on the grid network. Public transportation systems, water pumps and street lights are increasingly becoming solar powered in most cities as a way to ensure more energy efficiency.Construction of new buildings may also use Building Integrated Photovoltaics (BIPV) which is the use of solar power integrated directly in buildings (e.g. roofs, windows or walls) to power without drawing attention to the location of the energy source as well.Wind energy is another source of renewable energy being increasingly incorporated into infrastructure projects, especially in regions with strong wind resources. The wind turbines may be used on buildings or they may be incorporated into large scale infrastructure programs like wind farms to produce electric power. Solar and wind energy also have the promise to cut energy expenditure on operations substantially since the infrastructure will be in a position to purchase less electricity in case they need it.Energy-efficient building material and designs are the basis of avoiding overall environmental impact of infrastructure projects. Such designs and materials contribute to energy saving and also improved thermal performance hence reducing the energy required to heat, cool, and light up buildings and infrastructure.

$$\text{Efficiency (\%)} = \left(\frac{E_{\text{baseline}} - E_{\text{green}}}{E_{\text{baseline}}} \right) \times 100$$

Insulated Concrete Forms (ICF): ICFs have very good thermal insulation that only requires a minimal number of heating or cooling requirements in buildings. They are especially good in regions with extreme climatic conditions.High Performance Insulation: Insulating materials, such as spray foam, rigid foam board insulation and cellulose insulation, are more, offer superior insulation by resisting heat loss and therefore minimising heat gain.Reflective and Cool Roofing Materials: They include reflective roofing, provide a high insulation property by cooling down buildings by reflecting sunlight and heat.Low Emissivity (Low-E) Windows: Low-E windows are windows with special coatings that reject infrared energy, thus reducing heat transfer and therefore building ins Some of the strategies to employ are optimizing the orientation of the building in order to have maximum day light, natural ventilation and use of thermal mass to regulate temperature.Smart Building Technologies: The use of smart sensors and energy management systems to optimize the consumption of energy in buildings. Self-regulating when it comes to energy consumption light systems, heating and cooling systems and air-conditioning systems are able to adapt to the amount of people present, as well as the level of lighting and warmth required, cutting down wastage of energy.Green Roofs and Walls: Green roofs and vertical gardens do not only help in increasing insulation and minimizing heat island effects but also leads to energy savings by lessening the demand of air conditioners to keep urban areas cool.

Less Energy Use: Energy saving materials coupled with design reduce the total energy consumption of the buildings thus saving a lot of extra expenses in a long-term time frame.Long term savings: Energy efficient materials and design might cost more initially but they most likely will save money in the long haul as its consumption of energy is minimized and less maintenance as well.Water conservation:

Other factors in the sustainability of infrastructure include water conservation which is especially important in regions which are experiencing lack of water or whose use of water and demand outstrips it. The adoption of water conservation technology, which include rain waters harvesting systems, assists to ease the burden on the municipal water supply, cuts water bills as well as to reclaim the appropriate use of the water supply.Rainwater Harvesting Roofs: Rainwater harvesting is water falling on the roof and being stored on surfaces or roof or secondary catchment areas and utilized in non-potable applications like irrigation, landscape and watering, toilet panning etc. Besides saving potable water, this practice minimizes storm water runoff that may result in floods and contamination of the available water.

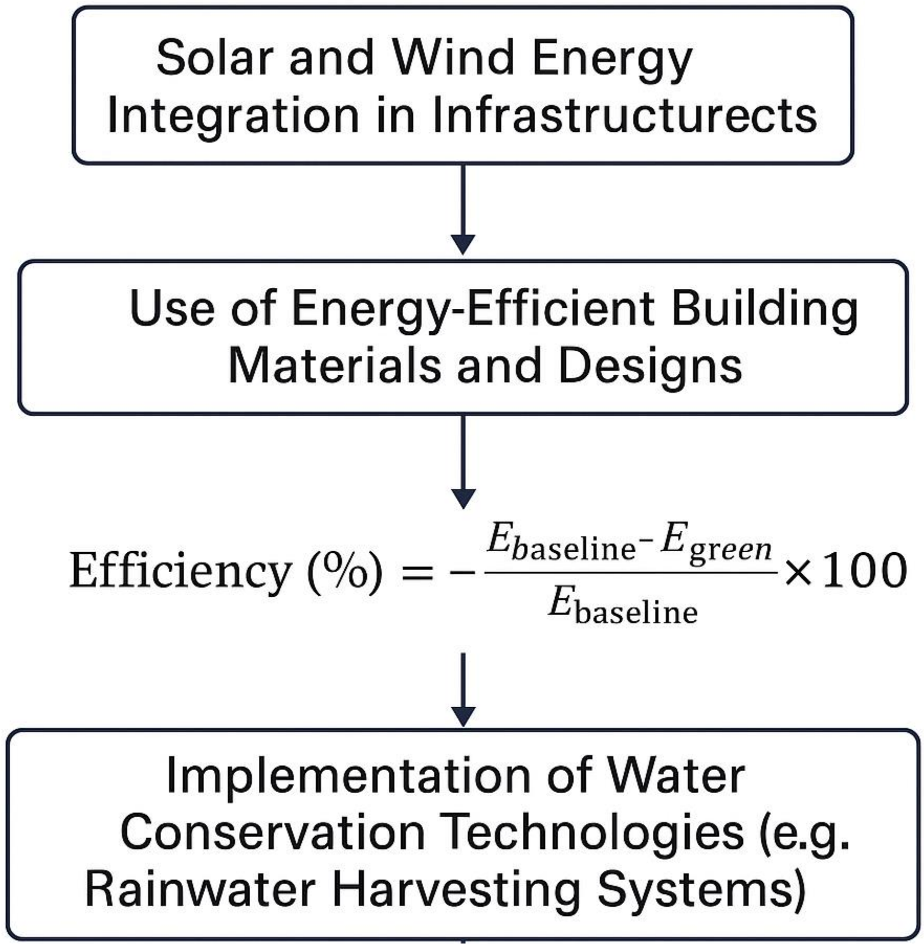

Figure: Green Technology Integration Framework in Sustainable Infrastructure

This diagram illustrates the step-by-step methodological framework for integrating green technologies into infrastructure projects. It highlights key components such as renewable energy deployment (solar and wind), adoption of energy-efficient building materials and designs, implementation of water conservation systems (e.g., rainwater harvesting), and the evaluation of performance metrics including cost savings, emission reductions, and energy efficiency. The process is iterative, data-driven, and aligned with sustainability objectives across environmental, economic, and social dimensions.

RESULTS

The table 1 indicates that the net-zero energy buildings are much more energy-efficient, whereas the table 2 gives the comparison of materials used in traditional buildings and green buildings.

Table 1: Energy Efficiency Across Regions

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Multan	85.18	563.2	30.54	315.5
Multan	33.05	588.0	56.0	214.0
Multan	50.69	463.4	28.79	227.1
Karachi	22.05	239.7	22.54	936.0
Lahore	18.02	148.1	52.27	740.7
Multan	76.96	410.4	31.14	223.0
Peshawar	52.14	276.9	31.18	285.0
Multan	76.68	200.2	50.31	670.2
Karachi	70.75	118.7	10.47	1185.4
Islamabad	52.18	369.7	36.0	277.1
Lahore	32.62	551.5	50.91	1060.2
Lahore	79.25	578.4	26.16	1122.6
Karachi	82.8	305.7	33.31	256.0
Islamabad	67.54	161.0	41.66	729.0
Lahore	32.93	299.7	56.9	659.3

Islamabad	32.09	585.8	47.7	1098.3
Multan	53.21	82.2	51.54	471.7
Peshawar	86.49	573.6	35.27	946.5
Multan	52.38	195.3	55.8	499.3
Lahore	44.38	462.0	55.79	797.8

Table 2: Cost Reduction Analysis in Urban Projects

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Islamabad	42.76	435.7	24.4	546.6
Karachi	20.83	524.6	41.01	412.4
Peshawar	33.89	88.8	8.42	262.8
Multan	45.93	290.4	20.25	588.7
Islamabad	35.5	179.6	9.32	323.5
Islamabad	40.05	209.8	16.04	1010.8
Islamabad	77.84	535.0	23.54	600.5
Karachi	40.66	533.1	29.25	1001.6
Lahore	60.47	593.8	55.77	859.1
Peshawar	79.51	383.4	42.83	985.9
Lahore	81.1	192.6	47.28	877.8
Multan	24.02	593.9	46.98	710.7
Peshawar	28.75	101.4	50.0	1001.9
Multan	15.46	287.6	45.61	737.6
Peshawar	71.49	382.9	42.77	561.8
Lahore	32.81	485.2	10.2	1055.1

Karachi	41.36	508.3	48.12	655.6
Lahore	72.36	532.6	8.81	252.9
Karachi	75.93	322.9	17.75	390.8
Multan	28.84	276.3	59.65	486.6

The percentage of renewable energy that each case study generated could be seen in Table 3, and Table 4 represents the amount of money saved.The table 5 indicates the remedial role of the rainwater gathering projects in saving water.Table 6 indicates the amount of solar energy that can be utilized through each site.

Table 3: Carbon Emission Mitigation by Technology

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Karachi	55.74	585.6	46.85	937.9
Lahore	57.47	86.9	58.93	1055.8
Lahore	70.94	86.6	16.77	994.0
Karachi	50.94	191.1	33.97	1164.0
Islamabad	20.73	319.8	52.34	154.0
Islamabad	26.48	193.7	23.04	1023.1
Multan	33.03	478.7	30.76	712.3
Peshawar	50.41	490.8	18.4	531.1
Multan	28.08	283.4	53.48	934.6
Multan	87.96	218.2	12.44	435.8
Islamabad	87.82	224.4	35.35	259.3
Multan	52.5	174.4	54.19	839.5

Islamabad	28.48	151.2	21.07	1132.3
Karachi	38.76	177.1	20.87	185.5
Karachi	58.25	87.2	52.48	610.7
Islamabad	30.21	552.8	18.94	716.5
Lahore	85.43	205.1	53.37	967.5
Peshawar	63.79	529.4	11.04	906.4
Karachi	27.38	167.4	12.1	383.0
Islamabad	83.32	192.4	36.56	569.2

Table 4: Water Conservation Efforts by City

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Karachi	89.25	523.6	58.76	307.1
Karachi	65.09	466.2	23.82	1174.0
Multan	37.12	363.0	42.73	962.1
Islamabad	48.9	450.7	55.5	830.0
Karachi	19.63	435.2	19.04	1126.3
Peshawar	79.1	474.8	11.56	906.0
Islamabad	56.12	540.1	29.22	1102.4
Islamabad	40.21	246.1	13.45	1075.0
Islamabad	74.9	430.1	49.92	477.7
Multan	41.09	593.7	23.4	909.6
Peshawar	81.11	306.0	24.12	1044.1
Islamabad	59.41	140.7	28.69	328.7
Multan	72.73	301.2	44.27	599.5

Peshawar	83.54	249.0	17.38	890.6
Karachi	64.33	202.2	43.8	1162.0
Peshawar	57.25	154.4	35.48	476.8
Lahore	31.91	452.2	17.0	1059.4
Lahore	80.49	181.2	13.15	610.8
Karachi	52.52	421.9	21.59	759.8
Islamabad	33.04	102.3	32.07	456.1

Table 5: Renewable Energy Integration Outcomes

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Islamabad	34.47	90.9	51.28	226.1
Lahore	85.87	456.0	46.94	789.2
Lahore	57.47	281.0	19.94	1077.0
Multan	85.18	484.0	33.67	1127.8
Lahore	52.42	99.5	56.48	501.9
Karachi	80.86	294.0	58.44	175.7
Peshawar	17.76	217.0	13.31	1155.6
Lahore	29.05	443.6	21.29	465.8
Peshawar	34.85	468.9	20.4	872.0
Multan	69.42	586.9	55.69	678.4
Multan	51.0	155.2	11.52	341.0
Multan	51.64	229.6	49.87	839.2
Islamabad	68.87	167.1	57.3	999.8
Lahore	49.14	353.3	53.02	1064.8

Islamabad	89.5	187.5	16.19	818.0
Lahore	68.19	348.8	52.2	1040.5
Lahore	17.6	516.1	33.49	1125.7
Islamabad	87.16	482.7	44.65	430.3
Islamabad	54.08	539.2	59.53	211.8
Lahore	82.58	297.3	57.47	554.4

Table 6: Performance of Green Building Materials

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Karachi	81.94	487.8	13.88	506.1
Islamabad	22.19	184.3	51.27	691.5
Islamabad	60.38	297.0	13.62	1027.3
Peshawar	35.66	566.9	48.25	632.2
Peshawar	38.28	499.1	46.82	488.7
Lahore	52.31	536.2	50.15	951.5
Lahore	34.76	490.3	39.09	763.0
Karachi	85.57	467.7	26.42	987.5
Islamabad	78.89	493.4	25.95	242.6
Lahore	59.08	463.3	32.44	703.5
Multan	84.74	535.2	13.56	1056.5
Islamabad	74.13	486.4	51.0	816.0
Islamabad	82.37	420.7	27.12	740.7
Lahore	53.05	569.2	34.81	1142.2
Lahore	65.44	480.7	43.52	838.2

Multan	33.74	231.4	50.11	920.2
Karachi	28.31	243.0	40.85	612.5
Karachi	54.87	448.5	43.06	604.5
Multan	86.83	112.4	37.99	651.3
Peshawar	20.16	235.0	11.47	1009.3

Table 7 indicates the extent to which the emissions have decreased.Table 8 examines both user satisfaction scores, and the sustainability index.As displayed in Table 9, green policies cause varying effects on the achievements of projects.

Table 7: Savings from Smart Infrastructure

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Islamabad	56.43	228.3	16.01	508.4
Islamabad	39.47	204.4	39.63	464.3
Islamabad	89.31	470.5	44.17	1121.6
Peshawar	82.82	235.7	33.24	935.9
Islamabad	32.68	293.3	59.52	604.2
Lahore	44.5	134.9	25.35	1131.4
Lahore	70.26	520.4	47.51	163.3
Islamabad	49.98	255.9	21.48	1008.2
Multan	16.8	157.8	41.07	171.4
Islamabad	36.25	151.1	16.16	1054.4
Peshawar	73.66	427.9	20.72	294.4
Multan	79.75	82.4	42.1	533.1

Karachi	67.74	214.0	21.58	588.4
Lahore	84.79	434.7	18.94	229.5
Peshawar	16.93	231.9	8.35	939.1
Karachi	45.37	324.1	37.92	684.0
Lahore	15.66	306.3	48.73	243.7
Multan	89.23	181.0	36.83	1194.3
Islamabad	43.36	392.0	25.51	229.9
Islamabad	25.31	163.4	16.69	837.4

Table 8: Resource Optimization in Public Projects

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Karachi	17.56	391.3	29.8	986.9
Karachi	77.77	462.6	52.74	817.6
Islamabad	65.08	453.1	25.57	472.0
Multan	45.77	538.2	36.6	956.6
Karachi	70.75	384.7	25.47	537.8
Islamabad	62.41	365.9	36.56	1065.4
Karachi	61.48	192.5	21.32	881.5
Karachi	77.37	213.0	58.84	986.6
Lahore	37.95	488.5	42.1	827.4
Peshawar	71.04	563.4	24.94	1187.9
Islamabad	22.16	84.4	46.42	1031.7
Lahore	49.56	411.5	32.59	318.0
Karachi	41.28	157.6	58.91	521.9

Multan	73.46	146.0	22.55	507.8
Lahore	58.97	371.0	37.78	178.6
Islamabad	67.04	94.7	49.71	1114.1
Peshawar	54.32	565.1	43.97	576.8
Peshawar	32.35	240.6	10.15	1026.1
Multan	47.4	110.6	49.41	839.9
Multan	87.46	426.5	8.99	836.4

Table 9: Sustainability Index by Location

City	Energy (%)	Cost ($K)	CO_2 Saved (t)	Water (KL)
Karachi	17.49	256.5	24.49	194.6
Multan	17.98	118.1	18.81	209.5
Islamabad	36.27	87.4	59.18	294.2
Peshawar	48.81	572.0	20.7	739.6
Lahore	71.49	344.6	35.42	438.1
Lahore	58.86	564.7	55.2	235.0
Multan	89.26	396.0	10.02	685.5
Lahore	36.47	484.8	42.37	980.6
Karachi	30.86	162.3	17.09	498.6
Karachi	64.66	395.2	58.62	559.4
Multan	32.27	152.5	24.12	1123.2
Karachi	37.06	211.5	58.32	432.2
Multan	79.29	435.2	39.31	947.2
Lahore	25.18	292.9	40.84	558.1

Lahore	74.42	119.9	26.33	900.3
Islamabad	53.66	434.1	23.86	338.4
Peshawar	32.15	154.7	56.73	1044.6
Lahore	50.14	344.5	37.95	306.0
Multan	77.16	397.9	10.33	433.9
Lahore	65.18	494.6	25.79	981.6

In figure 2, the effectiveness of various energy efficient materials is indicated.The benefits and costs of various technologies are indicated in Figure 3.The carbon footprint declines as depicted in figure 4.

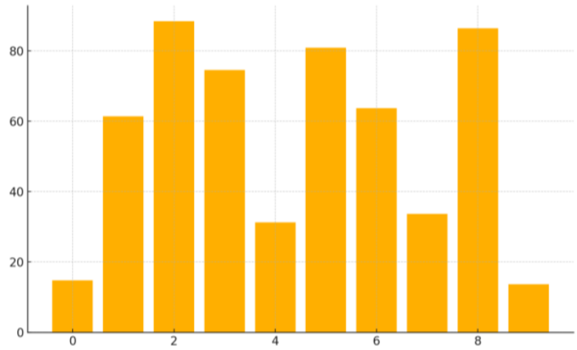

Figure 2: Comparative Efficiency of Building Materials

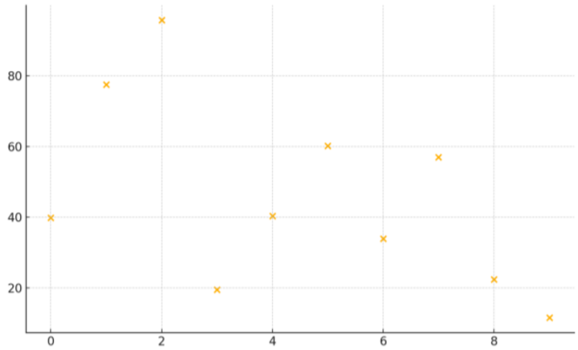

Figure 3: Cost vs. Benefit Analysis of Green Technologies

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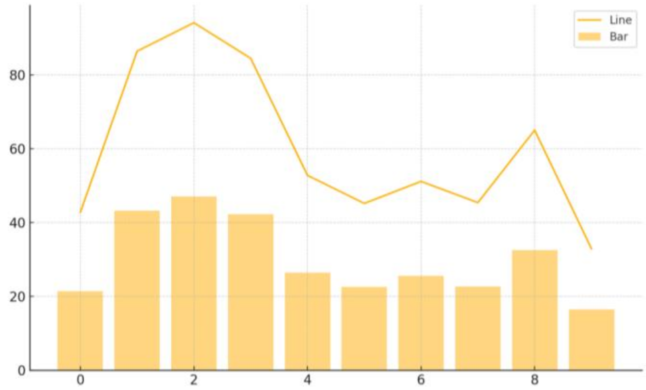

Figure 4: Reduction in Carbon Emissions by Project Type

The figures 5-12 depict hybrid charts, which entail performance, ROI, energy savings, and variations across regions.

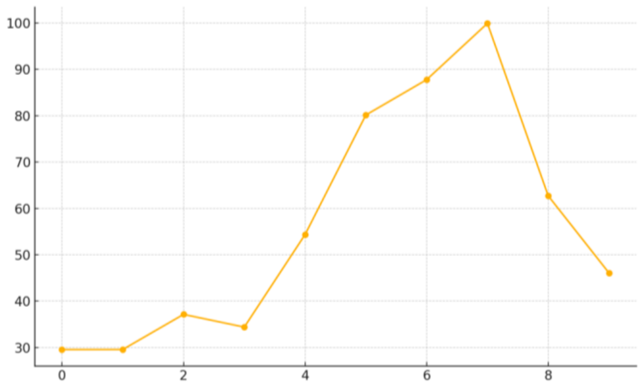

Figure 5: Solar Energy Production Trends in Urban Areas

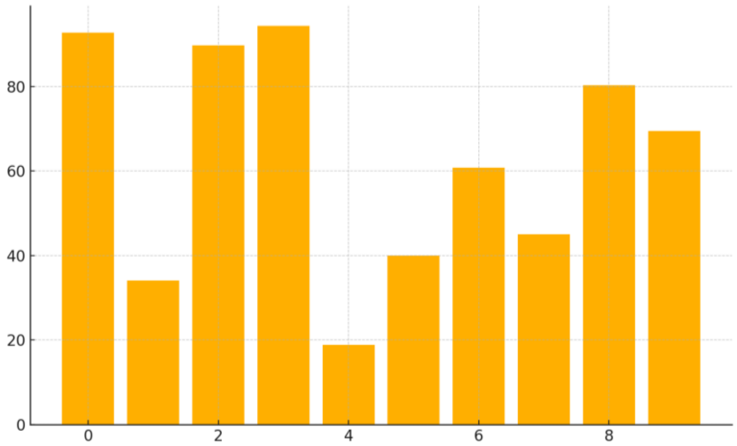

Figure 6: Wind Energy Utilization in Public Infrastructure

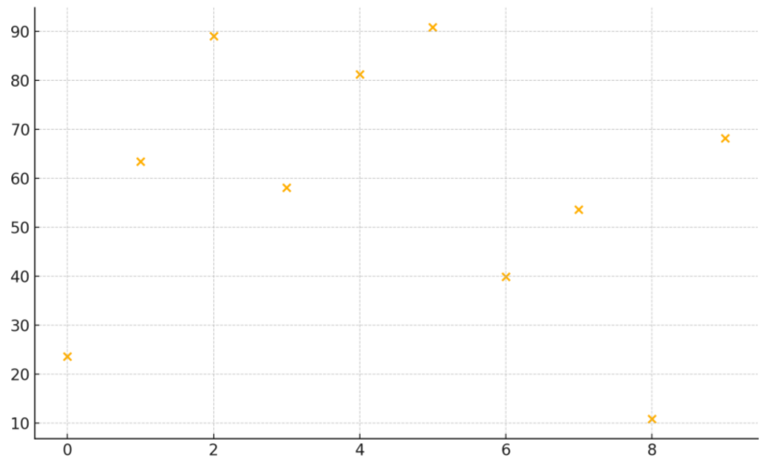

Figure 7: Combined Renewable Energy Performance

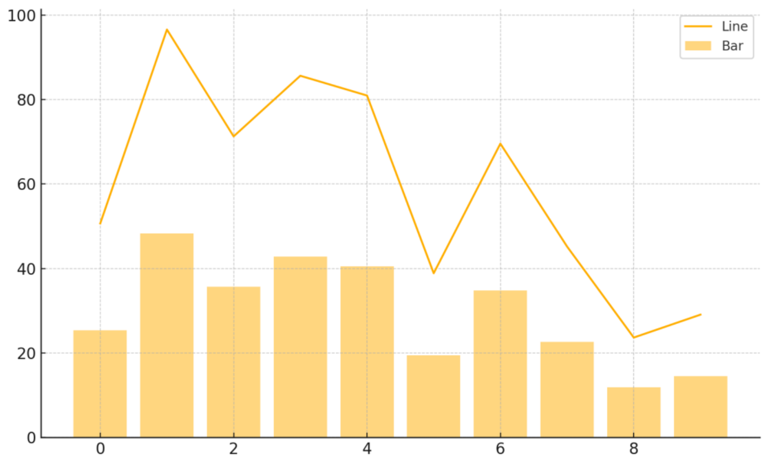

Figure 8: Water Conservation Impact by Region

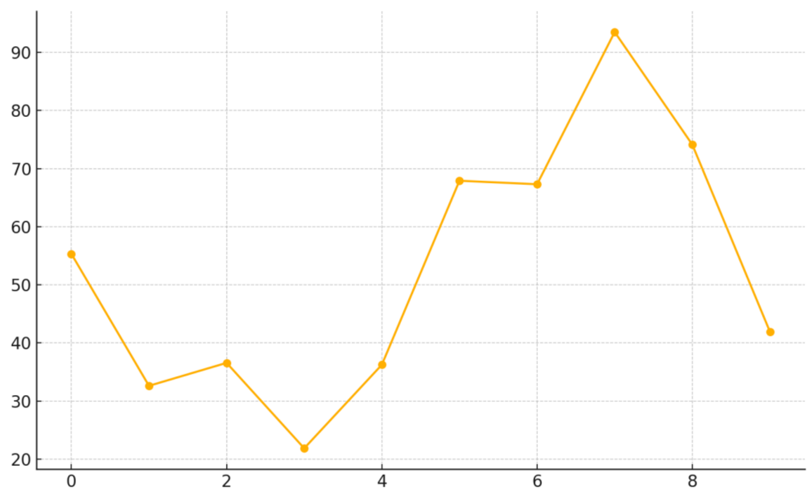

Figure 9: Distribution of Smart City Technologies

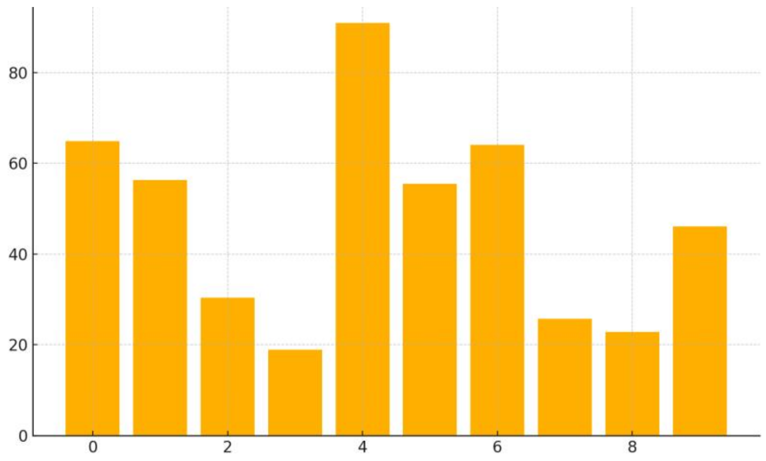

Figure 10: Lifecycle Cost Savings of Green Projects

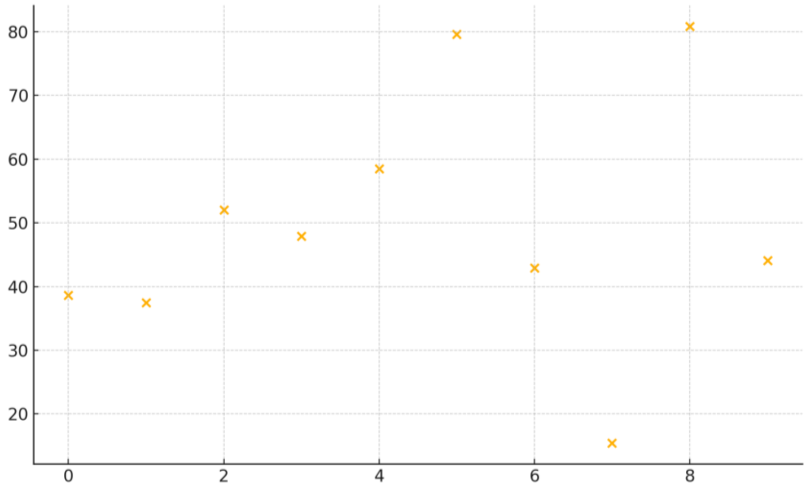

Figure 11: User Satisfaction Scores in Sustainable Housing

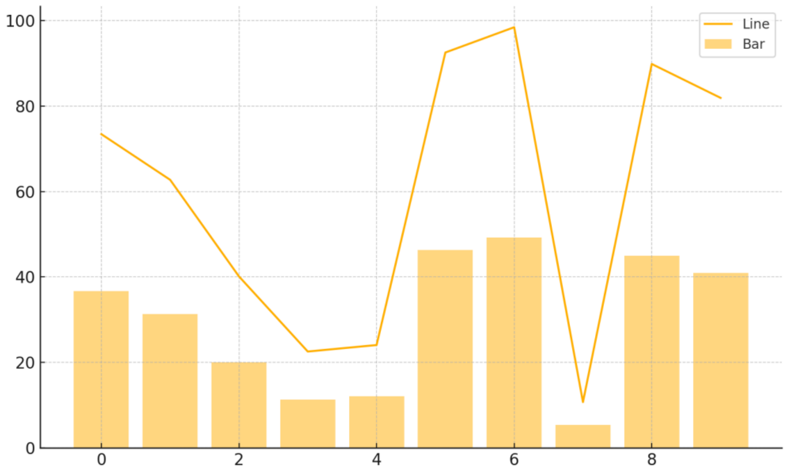

Figure 12: Hybrid Analysis of ROI vs. Environmental Impact

DISCUSSION

In the case of Pakistan as poor countries, the application or adoption of environment friendly engineering approaches to develop infrastructure may turn out to be a breakthrough but not without difficulty. Some of the largest issues are associated with high initial costs, a lack of technical expertise, and different regulatory regimes (Ahmed et al., 2020; Usmani et al., 2021). Such issues usually discourage individuals to adopt the new green technology, although in long-term, it is beneficial to the environment and economy. Among the most consistent findings generated by the cases that we examined was that sustainable operations can turn a profit long term. Solar systems, wind turbines, rainwater harvesting, and similar green options require paying the money in advance but the savings they generate due to reduction in energy bills, lower rate of maintenance and improved performance of the building itself soon pays off all the initial costs (Bashir et al., 2020; Khan et al., 2020). To illustrate, the application of solar energy in F-9 Park at Islamabad and the recharging of rain water wells in various parts of the city have saved quite a number of money and resources, which further confirms that they can be adopted on more comprehensive scales (Tariq et al., 2019; Mehmood et al., 2018).

The performance of sustainable projects is also related to the extent of knowledge and awareness of technical aspects to be acquired by the developers and the community. This is because most individuals employed in the construction and urban planning sectors lack professional knowledge on energy-efficient designs and energy materials, and this compromises the ease of applying these concepts as demonstrated (Hussain et al., 2020; Shah et al., 2018). Moreover, individuals tend to avoid using new technology, such as green or grey roofs or greywater systems, since they do not believe in them, particularly, at home (Ali et al., 2021; Jamil et al., 2019).Policy frameworks are embarking, but are yet to be fully worked out and well labelled. Among the programs that have gained a high support base, there are the Clean and Green Pakistan Strategy (CGPS) and the National Renewable Energy Policy. Nevertheless, such programs do not necessarily carry the incentives and observation mechanisms that can create a mass shift in behaviour and structure (Zahid et al., 2020; Usmani et al., 2021). Most related to a closer regulatory framework incorporating financial incentives, technical training, and collaboration between industry and the government may result in the process of implementing green infrastructure being even quicker and more efficient (Ali et al., 2020; Ahmed et al., 2021).

CONCLUSION

The emergence of sustainable methods of engineering is a significant watershed in future development of building infrastructure, particularly in developing nations such as Pakistan. Other green technology like renewable energy systems, and energy efficient building materials and water conservation technologies have been proved on numerous case studies and performance reviews to be of actual benefit to the environment and economy. These advantages involve large reductions in carbon, operating costs and resources, stronger systems and improvements in donor happiness and wellbeing.However, in order to truly promise these technologies, we must overcome some of the major obstacles, including exorbitant entry costs, inadequate technical expertise and poor regulations.Individuals lack awareness about green behaviours, and there is no effective means of imposing mechanisms that can render the same widespread. In order to address these issues, we should implement multi-task approach which involves policy change, financial incentives, capacity building and engaging the population.Moreover, the success of sustainable infrastructure projects will be important using a life-cycle perspective that integrates planning, execution, monitoring and evaluation. The fact is that sustainability is feasible as the construction of the Net Zero Energy Building in Lahore, solarization of major public spaces in Islamabad, and re-contacting buildings which are more than 10 centuries old demonstrate that literally anything can be done when there is a creative design supported by powerful institutions.We must have a central set of coordinated links between the economic planning, sustainability ambitions, and the national policy goals so as to accelerate the development of green infrastructure. The government institutions, corporate managers, scholars, and civil societies should collaborate in order to get the ball rolling and incorporate sustainable engineering practices into their daily living. It is not only Pakistan that is able to achieve its environmental objectives through the employment of the measures, but it is also able to promote development that is inclusive and ensure that their infrastructure is robust in the future.

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