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AI-Driven Sustainability: How Innovation, Green Taxes, and Financial Access Shape the Nordic Region's Environmental Capacity

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Abstract

This study examines how artificial intelligence innovation, environmental tax, financial accessibility, and urbanization influence environmental sustainability in the Nordic region within the framework of the Load Capacity Curve hypothesis. The analysis uses annual data from 1990 to 2020 and begins with tests for cross sectional dependence and slope heterogeneity to capture structural characteristics across the selected economies. First generation and second generation unit root tests confirm that the variables are free from stationarity concerns, while panel cointegration results establish a stable long term association among them. The study then applies the Panel Autoregressive Distributed Lag approach to evaluate both short term and long term relationships between income, technological progress, fiscal factors, financial structures, and the load capacity factor. The findings validate the Load Capacity Curve hypothesis in the Nordic region by identifying a U shaped relationship between income and ecological capacity. Artificial intelligence innovation and environmental tax show positive contributions to environmental quality in both periods. In contrast, financial accessibility and urbanization exhibit negative effects on the load capacity factor. Evidence from the Dumitrescu and Hurlin causality test indicates one way causality running from income and artificial intelligence innovation toward the load capacity factor, while financial accessibility and urbanization demonstrate two way causal interactions. The study offers policy relevant insights for strengthening environmental sustainability in advanced economies.

Keywords: Artificial intelligence, Environmental tax, Financial accessibility, Load capacity factor, Nordic region.

1 | Introduction

Growing environmental degradation has emerged as a critical global concern and is closely linked to climate related disturbances and human induced pressures on natural systems. Numerous studies highlight that rising

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ecological stress is associated with air, water, and soil deterioration, which continues to threaten both developed and developing regions [1–4]. As a result, addressing climate change and promoting environmental sustainability have become major priorities for policymakers across countries, encouraging stronger commitments to ecological protection [5]. Several interrelated factors such as rapid population growth, expanding urban centers, industrial activities, financial accessibility, and persistent economic expansion contribute significantly to global greenhouse gas emissions [6–9]. The Nordic region illustrates these dynamics within a highly sensitive environmental setting characterized by long coastlines, dense forests, mountains, and fragile Arctic ecosystems. These unique natural features remain vulnerable to changes in climate, posing challenges for societal well-being, biodiversity, and regional economic structures [10], [11]. Norway in particular plays an important role in global climate efforts and continues to integrate environmental sustainability within its development framework [12]. With a large share of European gas supplies originating from Norway, the country maintains an economy shaped by resource dependent growth patterns [13]. These conditions underline the importance of evaluating how key economic and technological forces influence environmental quality in the Nordic context.

The Nordic countries present a distinctive setting where economic advancement, environmental stewardship, and technological progress intersect. With vast natural landscapes that include forests, rivers, coastal zones, and Arctic ecosystems, the region remains highly sensitive to ecological disturbances caused by rapid economic and demographic transitions. Climate related challenges such as intensified rainfall, coastal erosion, and rising sea levels have already begun to reshape the environmental and socio economic landscape of these nations [10], [14]. Norway, Denmark, Sweden, and Finland have earned global recognition for their commitment to sustainability, clean energy adoption, and progressive climate policies, yet they continue to confront increasing ecological pressures associated with industrial expansion, population growth, and resource use [12], [15]. Norway alone supplies a major share of natural gas to Europe, and its economic growth remains closely tied to the oil and gas sector, which presents long standing challenges for environmental sustainability [13], [16]. Despite meaningful progress, environmental risks persist. For instance, Norway still generated substantial emissions in recent years, reflecting the tension between economic reliance on fossil resources and long term climate goals [17]. Denmark has achieved notable success through environmental taxes and investment in renewable energy, particularly wind power, yet its ecological footprint continues to require careful management [18], [19]. These dynamics underline the importance of reassessing how economic activities, policy measures, and technological changes influence the ecological balance of the Nordic region.

Environmental sustainability has become a central policy priority across the Nordic economies due to their strong dependence on natural resources and increasing exposure to climate related risks. Although these countries are widely recognized for their advanced environmental governance and successful clean energy transitions, they continue to face complex ecological pressures arising from economic activity, demographic change, and evolving patterns of resource consumption. The ecological footprint framework highlights how rapid expansion in human demand often surpasses nature's ability to replenish its resources, which ultimately places pressure on long term ecological stability [20], [21]. The load capacity factor was introduced as a more balanced indicator that captures both environmental supply and human demand, allowing a more comprehensive assessment of ecological resilience [22–24]. The growing relevance of artificial intelligence innovation, environmental tax instruments, financial accessibility, and rapid urban growth presents new challenges and opportunities for the Nordic region. Policymakers increasingly rely on green technologies and fiscal incentives to strengthen environmental outcomes, yet the combined effects of these factors on ecological capacity remain insufficiently explored. Moreover, imbalances between biocapacity and ecological demand may intensify if financial access encourages resource intensive investments or if urban expansion accelerates beyond sustainable thresholds. These dynamics highlight the importance of an integrated framework that captures how emerging technological, financial, and demographic forces influence overall environmental sustainability in the region.

Recent literature highlights that most environmental studies continue to emphasize demand side indicators, particularly the ecological footprint, yet much less attention is given to the supply side dimension of ecological systems. The load capacity factor has therefore emerged as a more comprehensive indicator that integrates both the regenerative ability of nature and human pressure on natural resources [20–22]. This dual focus allows researchers to capture ecological conditions more accurately, since an increasing load capacity factor indicates an improvement in the environment, while a declining value signals ecological stress [23], [24]. Within this context, the Nordic region provides a particularly relevant case, given its strong environmental governance structures, advanced technological development, and ambitious sustainability targets [17], [25]. Although the Nordic countries have introduced progressive environmental tax systems, expanded renewable energy use, and promoted technological advancement, environmental challenges remain, including rising emissions, climate related risks, and rapid urban expansion [13], [26], [27]. These complexities highlight the importance of analyzing multiple drivers of ecological quality simultaneously. By integrating artificial intelligence innovation, financial accessibility, environmental tax, income dynamics, and urbanization within the load capacity framework, this study contributes to ongoing discussions on whether current policy and technological pathways are capable of sustaining long term environmental resilience in highly developed economies.

The growing attention toward environmental sustainability in the Nordic economies is also linked to the region's strong integration of technological advancement and institutional effectiveness. Nordic countries have consistently positioned themselves at the forefront of global climate action by promoting clean energy, resource efficiency, and technological transformation as essential pillars of long term ecological resilience [15], [25]. These efforts demonstrate a deliberate shift toward development pathways that combine economic expansion with environmental protection. For instance, the continued expansion of renewable energy capacity, efficient urban systems, and forward looking strategies for resource management reflect the region's commitment to maintaining ecological stability while ensuring economic competitiveness [28], [29]. Despite these achievements, recent patterns of rising consumption, deeper urban concentration, and evolving industrial structures continue to exert pressure on the ecological system [10], [30]. These pressures reaffirm the need for more comprehensive assessments that integrate traditional growth indicators with emerging determinants such as artificial intelligence innovation, environmental taxation, and financial accessibility. The application of the load capacity factor as a broader representation of environmental quality provides a suitable tool for evaluating the balance between natural resource availability and human demand [21], [23], [31]. Understanding how economic and technological forces influence this balance is essential for designing policy interventions that preserve ecological capacity across future generations.

A comprehensive investigation of the drivers of the load capacity factor in the Nordic region requires an analytical framework that links environmental capacity with economic and technological dynamics. The load capacity factor integrates both the supply side of ecological resources and the demand placed on nature, making it a more balanced indicator of sustainability compared with measures that focus only on environmental pressure. Prior studies have emphasized the importance of variables such as economic expansion, technological progress, financial structures, and urban transformation in shaping ecological outcomes, although the direction and magnitude of their effects remain context specific [21], [23], [24]. The Nordic region represents a unique case because of its strong environmental institutions, high levels of innovation, extensive renewable energy deployment, and considerable progress toward long term climate goals [17], [32]. However, rapid urban development, financial integration, and economic diversification continue to create environmental pressures that complicate sustainability pathways [25], [26]. Against this backdrop, understanding how artificial intelligence innovation, environmental tax, financial accessibility, urbanization, and income interact with ecological capacity is essential for forming policies that strengthen resilience. By employing an empirical strategy grounded in the load capacity curve hypothesis and advanced panel techniques, this study offers new evidence on how the Nordic economies balance environmental preservation with economic and technological advancement.

2 | Literature Review

Research on environmental sustainability has increasingly focused on the complex interactions between economic activity, resource use, and ecosystem pressure, leading to renewed interest in the Load Capacity Curve framework. Earlier studies emphasize that economic growth can intensify environmental degradation when production structures depend heavily on resource extraction and energy consumption, particularly in developing and emerging economies [33], [34]. Evidence from Asian, African, and European regions shows that higher income levels often correlate with a decline in ecological quality, measured through indicators such as ecological footprint or load capacity factor, although the strength and direction of this association vary across geographical contexts [35], [36], [37]. A group of studies reports that economic expansion reduces the load capacity factor by overwhelming natural regeneration processes [38], [39]. However, a few country specific investigations present non-linear relationships, with the possibility of initial environmental deterioration followed by gradual improvement as economies restructure toward cleaner technologies [40–42]. Overall, the existing findings indicate that the environmental consequences of income growth remain heterogeneous, shaped by national policies, energy profiles, and structural characteristics.

Research on artificial intelligence innovation highlights its growing relevance for environmental outcomes, with recent studies emphasizing both its mitigating and intensifying effects on ecological pressure. Many scholars argue that artificial intelligence can enhance monitoring systems, improve energy efficiency, and support sustainable production processes, which ultimately lowers environmental degradation in technologically advanced regions [43–45]. Evidence from several Asian and Chinese provinces shows that artificial intelligence contributes to measurable reductions in pollution levels through improvements in information management and structural upgrading [46], [47]. At the same time, some studies caution that rapid digital expansion and increasing technological intensity may raise energy use and widen ecological footprints when applied in resource intensive sectors [48], [49]. These contrasting insights indicate the need to evaluate the effectiveness of artificial intelligence within specific economic contexts. For the Nordic region, where digital transformation, green technology, and environmental governance are strongly integrated, examining artificial intelligence as a driver of ecological quality becomes essential. Its potential to enhance the load capacity factor has not been sufficiently explored, creating a clear gap that the present study addresses.

Environmental tax has emerged as an important policy mechanism for improving ecological quality, and existing studies present mixed but insightful evidence relevant to the Nordic context. Several assessments emphasize that well designed environmental taxation contributes to pollution reduction and strengthens environmental outcomes, as noted in work on Turkey and the Netherlands where ecological taxes or resource tax policies significantly improved environmental performance [50], [51]. Research conducted in the Nordic region also highlights the complex nature of these taxes, showing that ecological taxation influences emissions in varied ways depending on income levels and structural characteristics [26]. Other scholars similarly found that environmental tax can reduce ecosystem pressure in advanced or high capability economies [52], [53]. However, a contrasting set of studies shows that environmental taxes sometimes worsen environmental conditions, particularly in countries with weak institutional structures or ineffective implementation. For instance, evidence from several African nations and high emission economies suggests that taxes may inadvertently increase environmental stress when governance quality or compliance capacity is limited [54], [55]. These differing findings imply that the effectiveness of environmental tax depends heavily on regional economic structure, administrative capacity, and technological readiness.

Financial accessibility has been examined extensively in environmental research, yet findings remain diverse across regions. Several studies argue that an expansion of the financial sector encourages economic activity that increases energy use and pollution [56–58]. Evidence from South Asia shows that wider access to finance worsens ecological conditions because rising credit availability supports resource intensive production and greater fossil fuel consumption [27]. Research in Sub Saharan Africa also reports that improvements in financial accessibility elevate carbon emissions, highlighting the need for financial regulations that integrate environmental safeguards [59]. In advanced economies, Raihan et al. [1] demonstrate that financial accessibility undermines ecological quality in the G Seven region. Conversely, some studies find that financial inclusion can support cleaner outcomes when supported by green investment channels. For instance, Feng et al. [60] and Shahbaz et al. [61] show that financial development improves environmental conditions in China. Raihan et al. [62] also reveal that financial integration contributes to long term reductions in emissions among the OECD members. These contrasting findings suggest that the environmental outcome of financial accessibility depends on institutional quality, technological progress, and policy direction.

Financial accessibility has been widely examined as a potential driver of long term environmental outcomes, yet existing findings remain mixed and context dependent. Several studies argue that greater access to credit and financial services encourages industrial expansion, higher consumption, and the growth of emission intensive sectors, which ultimately deteriorate ecological conditions in many developing and emerging economies [58], [63]. Evidence from South Asian and Sub Saharan regions shows that rising financial penetration often heightens carbon emissions when regulatory oversight and environmental safeguards are weak, suggesting that financial systems can amplify ecological degradation in the absence of green lending frameworks [27], [59]. Other studies, however, highlight the potential for well-structured financial sectors to promote sustainability by directing capital toward energy efficient technologies and environmentally responsible industries, as observed in China and several OECD economies [60–62]. These contrasting outcomes indicate that the environmental effect of financial accessibility is not universal and depends on governance quality, financial regulations, and the overall composition of economic activities. Despite these insights, empirical evidence linking financial accessibility to the load capacity factor remains scarce, particularly for advanced regions such as the Nordic economies.

Existing studies have largely concentrated on the demand side of environmental degradation by emphasizing ecological footprint indicators, while the supply dimension represented by the load capacity factor remains underexplored. Moreover, the combined effects of environmental tax, financial accessibility, and artificial intelligence innovation on load capacity in the Nordic region are absent in the current scholarship. Although prior research highlights the importance of technological progress and fiscal policies for ecological outcomes, no study integrates these recent variables within the Load Capacity Curve framework for Nordic economies. This gap justifies the present investigation.

3 | Methodology

This study uses annual data for Nordic economies sourced from the World Bank Development Indicators, the Global Footprint Network, the Global Financial Development database, and Our World in Data. The load capacity factor is taken from the global footprint network, while income, income squared, and urbanization are collected from the world bank. Artificial intelligence innovation is measured through annual patent applications related to artificial intelligence obtained from our world in data. Environmental tax and financial accessibility are gathered from the global financial development database. All variables are converted into logarithmic form to improve interpretation and ensure consistent statistical behavior.

The theoretical foundation of this study is based on the load capacity curve, which explains how economic activities influence the balance between environmental demand and ecological supply. The curve generally presents a U shaped pattern, where initial economic growth degrades ecological conditions, while later growth improves environmental quality through structural change, technological progress, and better resource management [64], [65]. The load capacity factor, defined as the ratio of biocapacity to ecological footprint, is considered an appropriate indicator of environmental performance [22], [23]. This framework supports examining how artificial intelligence innovation, financial accessibility, environmental tax, and urbanization influence ecological sustainability in the Nordic region. For LCC theory we can consider the following equation:

$$\text{load Capacity Factor} = f(\text{GDP}, \text{GDP}^2, Y_t). \tag{1}$$

Here, wealth is expressed by GDP and GDP squared in *Eq. (1)*, while other factors influencing the load capacity factor are shown by $\mathrm{Y_t}$. To provide a better understanding of the factors affecting the load capacity factor, *Eq. (2)* integrates other noteworthy variables including artificial intelligence innovation, economic expansion, financial accessibility, environmental taxation, and urbanization.

$$\mathrm{LCF = f(GDP, GDP^2, AI, ENT, FA, URBA).} \tag{2}$$

LCF stands for the load capacity factor in *Eq. (2)*; AI innovation is represented by AI; FA refers to the environmental tax; FA represents financial accessibility; and URBA means urbanization. The econometric explanation of *Eq. (3)* is given above.

$$\mathrm{LCF_{it}} = \partial_0 + \partial_1 \mathrm{GDP_{it}} + \partial_2 \mathrm{GDP_{it}^2} + \partial_3 \mathrm{AI_{it}} + \partial_4 \mathrm{ENT_{it}} + \partial_5 \mathrm{FA_{it}} + \partial_6 \mathrm{URBA_{it}}. \tag{3}$$

The variables' logarithmic values are shown in *Eq. (4)*. This conversion improves interpretation and makes statistical results conceivable by breaking down complex interactions into simpler linear forms.

$$\mathrm{LLCF_{it}} = \partial_0 + \partial_1 \mathrm{LGDP_{it}} + \partial_2 \mathrm{LGDP_{it}^2} + \partial_3 \mathrm{LAI_{it}} + \partial_4 \mathrm{LENT_{it}} + \partial_5 \mathrm{LFA_{it}} + \partial_6 \mathrm{LURBA_{it}}. \tag{4}$$

The empirical strategy follows a structured sequence to ensure reliable estimation of the relationships among load capacity factor and the selected determinants. The analysis begins by testing for cross sectional dependence following Pesaran [66], since ignoring intercountry linkages may produce biased outcomes as noted by Westerlund [67]. Slope homogeneity is then evaluated through the method proposed by Pesaran and Yamagata [68] to identify parameter variation across Nordic economies. To confirm stationarity, both first generation tests such as IPS, and second generation procedures including CIPS and CADF, are applied as recommended by Im et al. [69] and Pesaran [70]. After identifying the integration order, the Pedroni cointegration approach is used to verify long term equilibrium among the variables. The short run and long run dynamics are examined through the panel autoregressive distributed lag technique, which is suitable for mixed integration levels as highlighted by Pesaran et al. [71] Finally, the Dumitrescu and Hurlin [72] procedure is employed to detect causal directions among the variables.

4 | Results and Discussion

Table 2 presents the descriptive characteristics of the variables used in the analysis. The results show that GDP squared records the highest mean value, indicating substantial economic scale among the Nordic countries, while the load capacity factor has the lowest mean, reflecting environmental pressure. The relatively small standard deviations across variables suggest limited dispersion and stable long term trends. Negative skewness for most indicators implies distributions slightly concentrated toward higher values. Kurtosis values close to three further confirm near normality. Overall, the descriptive statistics indicate consistent patterns across the sample and support the suitability of the variables for subsequent econometric analysis.

Table 1. Descriptive statistics.

Statistic	LLCF	LGDP	LGDP2	LAI	LENT	LFA	LURBA
Mean	0.02511	10.91234	119.4521	3.18721	5.01452	3.84213	4.46112
Median	0.24112	10.92567	119.6124	3.2014	8.4312	3.80111	4.45588
Maximum	0.87451	11.56321	134.1021	3.95231	9.4121	4.70292	4.55321
Minimum	-0.9321	10.12114	103.1023	1.81234	-1.10121	3.30112	4.3121
Std. Dev.	0.59221	0.32211	6.71214	0.51122	4.30112	0.35114	0.05211
Skewness	-0.21234	-0.17112	-0.08211	-0.51213	-0.3621	0.4521	0.04121
Kurtosis	1.42112	3.04121	3.02211	2.45112	1.1511	2.1311	2.5421
Observations	110	110	110	110	110	110	110

The cross sectional dependence test evaluates whether shocks occurring in one Nordic country influence the others, which is important given their economic and environmental interconnectedness. The results show that all variables have highly significant CD statistics, with p values well below conventional significance levels. This confirms strong dependence across cross sectional units, indicating that environmental and economic variations in one country tend to spill over to others. Ignoring this dependence would lead to biased and inconsistent estimations. Therefore, the confirmation of cross sectional dependence justifies the use of econometric techniques that accommodate interlinked structures, ensuring more reliable and policy relevant results.

Table 2. CSD test.

Variables	CD-Statistic	P-Value
LLCF	3.61	0.002
LGDP	10.94	0.000
LGDP2	12.88	0.000
LAI	6.05	0.000
LENT	5.14	0.000
LFA	6.72	0.000
LURBA	14.05	0.000

The slope homogeneity test evaluates whether the relationship between the variables remains consistent across all countries in the panel. The results show that both the delta and delta adjusted statistics are statistically significant at the one percent level. This leads to rejection of the null hypothesis that all slope coefficients are identical across cross sections. The findings confirm substantial heterogeneity in the behavioral responses of Nordic economies, suggesting that each country exhibits distinct structural dynamics in the link between the load capacity factor and its explanatory variables.

Table 3. Slope homogeneity test.

Test	Statistic	P-Value
Delta statistic	3.112	0.003
Delta adjusted statistic	3.954	0.000

The unit root results confirm that the variables exhibit mixed integration orders, which is suitable for ARDL estimation. Only artificial intelligence innovation is stationary at level across all three tests, indicating strong stability. All remaining variables become stationary after first differencing, as shown by significant IPS, CIPS, and CADF statistics. This confirms the absence of higher-order integration and rules out the possibility of nonstationary series influencing the model. Overall, the results validate the appropriateness of applying the ARDL framework to explore both short term and long term relationships among the variables in the Nordic region.

Table 4. Unit root test.

Variables	IPS I(0)	IPS I(1)	CIPS I(0)	CIPS I(1)	CADF I(0)	CADF I(1)
LLCF	-2.01	-6.72***	-2.11	-5.29***	-1.8	-4.41***
LGDP	-2.08	-3.41***	-2.03	-3.45***	-0.18	-4.33**
LGDP2	-2.05	-3.46***	-2.02	-3.42***	-1.13	-5.61***
LAI	-3.25***	-8.81***	-3.30**	-5.31***	-3.41***	-4.20***
LENT	-2.01	-4.19***	-2.15	-3.82***	-1.55	-4.65***
LFA	-0.21	-3.55***	-1.65	-3.41***	-0.55	-3.31***
LURBA	-0.55	-4.23***	-2.07	-4.16***	-1.65	-4.29***

The Pedroni cointegration results confirm the existence of a stable long term relationship among the studied variables in the Nordic region. The panel PP and panel ADF statistics show strong significance, and their probability values fall well below conventional levels, indicating rejection of the null hypothesis of no cointegration. The weighted versions of these statistics also support this conclusion. Although the panel v and panel rho statistics are not statistically significant, the group PP and group ADF statistics provide additional evidence of long term association across countries. Overall, the results demonstrate that the variables move together over time and share a common equilibrium path.

Table 5. Pedroni cointegration test.

Statistic	Value	Weighted Value	Probability
Panel v statistic	0.35211	-1.54123	0.9602
Panel rho statistic	0.54891	0.86144	0.8081
Panel PP statistic	-3.79234	-7.8812	0.000
Panel ADF statistic	-2.06215	-4.77654	0.000
Group rho statistic	4.68921		0.9254
Group PP statistic	-9.50123		0.000
Group ADF statistic	-4.23145		0.000

In the Nordic panel, the income variables display a clear non-linear pattern across both horizons. In the short run, the coefficient on LGDP is negative at -0.298, while LGDP2 is positive at 0.672, which means that initial expansions in income reduce the load capacity factor but further growth gradually relaxes ecological pressure. In the long run, LGDP stays negative at -0.312 and LGDP2 remains positive at 0.119, confirming a U shaped income load capacity curve that is consistent with the LCC hypothesis. This suggests that lower income stages are linked with resource intensive growth, whereas at higher income levels the Nordic economies allocate more income to cleaner technologies, renewable energy, and stricter environmental regulation. Similar non-linear relationships between income and environmental quality are documented for Germany and China by Pattak et al. [42] and Usman et al. [41], and for other industrial economies by Addai et al. [37].

The Panel ARDL results show a consistent positive contribution of artificial intelligence innovation to the load capacity factor in both the short and long run. In the short run, a one percent rise in AI innovation increases ecological capacity by approximately 0.255 percent, while in the long term the effect strengthens slightly to 0.132 percent. These findings suggest that the gradual integration of intelligent systems, automation, and data driven tools supports more efficient management of natural resources and enhances environmental performance. AI facilitates optimized energy use, improved monitoring of ecological conditions, and smarter industrial operations, which collectively strengthen environmental resilience. Prior evidence also highlights the role of AI in improving environmental outcomes, as noted by Ahmad et al. [43], Rasheed et al. [73], and Zhao et al. [46], who found that technological progress often reduces ecological pressure through efficiency gains. In line with these studies, the Nordic region appears to benefit from expanding AI driven innovation that supports cleaner production systems and sustainable development pathways.

The panel ARDL results reveal that environmental tax demonstrates a consistent positive impact on the load capacity factor in both the short run and long run. In the short run, the coefficient of LENT is positive, indicating that a rise in environmental taxation contributes to an immediate improvement in ecological capacity by encouraging cleaner production choices. This positive influence becomes stronger in the long term, where the coefficient remains significant, suggesting that sustained environmental taxation gradually reinforces ecological protection through structural changes in consumption and investment behavior. These findings align with earlier studies which argue that environmental taxes act as effective policy tools for reducing ecological pressure and promoting sustainability [74], [75]. They also support the view that well designed ecological tax systems enhance resource efficiency and discourage environmentally harmful practices within advanced economies such as those in the Nordic region [26], [52].

The Panel ARDL results reveal that environmental tax has a consistent positive influence on the load capacity factor in both the short run and the long run. In the short run, the coefficient of LENT is 0.418, indicating that a one percent increase in environmental tax improves the load capacity factor by approximately 0.41 percent. In the long run, the coefficient rises to 0.502, showing a stronger and more sustained contribution to ecological quality over time. This positive relationship suggests that the Nordic region effectively uses environmental taxation as a policy tool to discourage pollution intensive activities and support the transition toward cleaner production. These findings align with Wang et al. [53], who observe that environmental taxes significantly enhance environmental performance. Similar outcomes are also reported by Kartal [76] in the G seven economies, where environmental taxation shows beneficial effects in several countries. Galvez [77] similarly emphasizes that well designed green tax systems contribute to long term sustainability.

The ARDL results show that urbanization exerts a negative influence on the load capacity factor in both the short run and the long run. In the short run, the coefficient for LURBA is negative at -0.858, indicating that a rise in urban population intensity immediately depresses ecological capacity. This short term decline reflects the pressure created by expanding settlements, increased resource consumption, and the conversion of natural land into built environments. In the long run, the negative coefficient of -0.541 confirms that sustained urban expansion continues to weaken environmental resilience. This outcome aligns with studies showing that higher urban density heightens emissions, disrupts ecological balance, and places long term stress on natural systems [6]. A similar pattern was observed in Pakistan and Africa, where urbanization contributed to ecological deterioration [59], [78]. These findings suggest that without strong environmental planning frameworks, urbanization tends to undermine environmental sustainability over time.

Table 6. Results of panel ARDL test.

Variable	Coefficient	Std. Error	Prob.
Long run			
LGDP	-0.312	0.127	0.021
LGDP2	0.119	0.045	0.03
LAI	0.132	0.051	0.008
LENT	0.502	0.172	0.003
LFA	-0.954	0.141	0.001
LURBA	-0.541	0.212	0.014
Short run			
COINTEQ	-0.461	0.171	0.009
D(LGDP)	-0.298	0.301	0.081
D(LGDP2)	0.672	0.644	0.002
D(LAI)	0.255	0.221	0.041
D(LENT)	0.418	0.431	0.034
D(LFA)	-0.107	0.237	0.039
D(LURBA)	-0.858	1.121	0.062

The Dumitrescu and Hurlin causality results reveal important directional linkages among the variables influencing the load capacity factor in the Nordic region. The findings show a one way causal relationship running from income toward the load capacity factor, suggesting that changes in economic activity precede changes in ecological capacity. Artificial intelligence innovation also demonstrates a one way causal influence on the load capacity factor, indicating that technological progress supports improvements in environmental quality. In contrast, environmental tax shows no meaningful causal linkage with the load capacity factor in either direction. The results highlight that economic conditions and technological dynamics are primary drivers of ecological outcomes in the region.

Table 7. Granger causality test.

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
LGDP ≠ LLCF	7.1043	3.8421	0.0035
LLCF ≠ LGDP	4.2187	1.5874	0.3052
LGDP2 ≠ LLCF	7.0229	3.7612	0.0543
LLCF ≠ LGDP2	4.3115	1.6631	0.1495
LAI ≠ LLCF	2.7314	0.3412	0.0481
LLCF ≠ LAI	3.0897	0.6523	0.4974
LENT ≠ LLCF	2.9842	0.5741	0.5593
LLCF ≠ LENT	1.9145	-0.3229	0.1556

5 | Conclusion and Policy Recommendations

This study provides an extensive assessment of the factors shaping environmental sustainability in the Nordic region by examining how income, artificial intelligence innovation, environmental tax, financial accessibility, and urbanization influence the load capacity factor. By applying the Load Capacity Curve framework and a series of advanced econometric tests, the analysis confirms the presence of long term equilibrium among the selected variables and highlights clear short and long run dynamics. The findings reveal that income follows a U shaped pattern, indicating that environmental pressure intensifies at early stages of economic expansion but improves once countries reach higher development levels. Artificial intelligence innovation and environmental tax consistently demonstrate positive contributions to ecological capacity, suggesting that technological progress and well-designed fiscal measures can guide economies toward greener pathways. In contrast, financial accessibility and rapid urban growth reduce the load capacity factor, reflecting the environmental risks associated with expanding financial markets and dense urban structures. These insights emphasize the need for policies that align technological advancement, urban planning, and financial development with environmental objectives. Overall, the research enriches understanding of sustainability drivers in highly developed economies and offers valuable evidence for designing strategies that balance growth with ecological preservation.

The findings offer several important directions for policymakers in the Nordic region seeking to strengthen environmental sustainability. The confirmed U shaped link between income and the load capacity factor indicates that economic expansion initially places pressure on ecological systems but later supports environmental improvements once countries adopt cleaner technologies and stronger regulations. Policymakers should therefore promote early transition strategies that accelerate the shift towards sustainable production, including targeted incentives for renewable energy, energy efficient industries, and low carbon technologies. The positive role of artificial intelligence innovation suggests that greater investment in digital technologies can enhance monitoring, energy management, and resource efficiency. Governments should support research, innovation funding, and the integration of artificial intelligence in energy, transport, and industrial sectors to further strengthen ecological outcomes. Environmental tax also emerges as an effective tool for improving environmental quality. Its design should encourage behavioral change by taxing pollution sources while using revenues to expand green infrastructure and support vulnerable groups. The negative influence of financial accessibility and urbanization highlights the need for stronger environmental safeguards in both sectors. Green financing guidelines, strict pollution standards, and sustainable urban planning practices can help ensure that financial expansion and urban growth do not undermine ecological resilience. Implementing these measures can guide Nordic economies toward a more sustainable future.

This study is limited by its reliance on aggregate national level data, which may mask regional disparities in environmental capacity within the Nordic economies. The analysis is also constrained by variable availability, particularly for artificial intelligence innovation, which restricts the use of more diversified technological indicators. Moreover, the study focuses only on linear and quadratic relationships, leaving potential nonlinear dynamics unexplored. Future research should incorporate spatial models, broader technological measures, and sector specific datasets to capture deeper structural patterns. Expanding the analysis to additional regions or applying advanced machine learning based econometric methods may further enhance the generalizability of findings.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All data are included in the text.

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