

Integrating Green Building into National Defense Systems

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Abstract — In the context of the dynamic security environment, the transition to energy independence of military infrastructure is becoming a strategic priority. However, the modernization of military facilities faces a critical conflict between traditional construction requirements for physical protection and modern sustainability standards. The study proposes a methodology for tracking the long-term effects of “green” solutions on the operational readiness of defense systems. The study contributes to the development of a strategic framework for sustainable decision-making in the defense sector. The results provide guidance for strategic planners and policymakers, arguing that the integration of sustainable technologies is essential for maintaining combat readiness in an environment with limited resources and high threat levels.

Keywords — *energy autonomy, defense infrastructure, strategic planning, sustainable development.*

I. INTRODUCTION

In today’s dynamic security environment, critical infrastructure is emerging as a fundamental pillar of national defense, determining both operational capacity and long-term sustainability of state systems [1]. Against the backdrop of the global energy transition, military organizations are faced with the need to adapt their facilities to environmental sustainability standards without compromising their core mission of ensuring security [6] – [7]. Despite the growing importance of this process, there is a serious deficit in the theoretical and practical understanding of “green” construction in the context of the defense sector [8].

The analysis of existing research approaches reveals a significant gap between standard energy efficiency models and the specific requirements of military infrastructure [2]. Similar challenges related to resilient, adaptive and uninterrupted power supply systems have also been identified in smart urban infrastructures, where energy continuity is essential for critical public functions [28]. Traditional frameworks, developed primarily for civilian sites, often ignore critical parameters such as the need for specific physical protection, cyber resilience of energy networks, and the requirements for full autonomy in critical situations [4] – [5]. It is this discrepancy that creates a serious obstacle to the effective implementation of modern environmental standards, since their implementation by mechanically copying civilian practices carries a risk to operational readiness [9].

This study aims to bridge this conceptual gap by developing an integrated approach to align security objectives with sustainable construction principles [10]. The main task focuses on defining a decision-making model that balances the requirements for a high level of protection with the need to optimize the environmental footprint [11]. Comparable management approaches have been explored in emergency response environments, where algorithmic coordination models are used to improve decision speed, resource deployment and operational effectiveness under high uncertainty [26]. Comparable sustainability governance challenges have been studied in corporate environments, where information systems are required to monitor environmental performance,

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accountability and reporting processes [27]. By examining the complex interdependencies between infrastructure sustainability and military capability, the study offers strategic planning guidelines that transform green investments into a real strategic asset, rather than simply complying with environmental regulations [12].

The conceptual evolution of military infrastructure reflects fundamental transformations in contemporary national defense strategy [13]. Historically, military facilities have been designed as static, centralized objects whose primary function was to concentrate resources and personnel in areas with a high degree of physical protection [14]. However, with the development of modern technologies, the focus has gradually shifted from static resilience to dynamic adaptability and operational autonomy [3]. Contemporary scientific literature emphasizes that the future of defense systems lies in the transition to intelligent, energy-independent facilities that are capable of functioning in interrupted supply chains [15]. This transformation process places new emphasis on the need to design bases that not only serve as operational centers, but also function as self-sufficient ecosystems capable of ensuring the continuity of vital processes in conditions of intense conflict [16].

In the context of energy efficiency, international standards for sustainable construction such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) occupy a central place in the construction industry [17]. These methodologies have proven their effectiveness in reducing the carbon footprint and optimizing operating costs in the civilian sector [18]. However, a critical analysis of the existing literature reveals serious limitations in their direct application in the defense sector [19]. Military facilities operate in an environment that requires specific levels of cybersecurity, resistance to targeted impacts and the capacity to operate under information blackout conditions, parameters that are often absent or insufficiently represented in civilian certification systems [20]. Similar risk-based approaches have been applied in the management of electrical distribution assets, where infrastructure reliability under uncertainty is a primary objective [25]. Moreover, the strict requirements for operational confidentiality and the specific construction materials needed to protect critical assets often come into direct conflict with some of the “green” recommendations for open architectural spaces or specific ventilation systems set out in LEED and BREEAM [21]. Therefore, the existing scientific base highlights the need for an adapted framework (Figure 1) that integrates sustainable construction principles into the specific operational paradigms of national defense, without compromising protection and reliability requirements [22]. The conceptual framework of the study is presented in Figure 1. Specific requirements of military infrastructure (physical protection, cybersecurity, autonomy) are reflected. Civilian sustainability standards (LEED, BREEAM), which conflict with traditional requirements, are also visualized. The bridge presents the developed three-stage methodology - modified Delphi, Best-Worst Method and Cook model

with Monte Carlo, which generates 6 economic criteria with weights (C1-C6, Tables 1 and 2) and 4 security scenarios (S1-S4, Table 5). The lower part summarizes the results: the hybrid alternative A2 dominates in crisis (S2) and local conflict (S3), while Net-Zero (A3) is only positive in complete disruption (S4).

II. MATERIALS AND METHODS

To achieve the goal of this study - integrating green building principles into national defense systems through economically sound solutions - a three-stage methodology (Figure 2) based exclusively on expert assessments has been developed. The choice of this approach is dictated by the specific features of the military sector: the lack of long-term market data on the costs and benefits of green technologies in defense facilities, the high degree of uncertainty associated with future security scenarios, as well as the need to take into account qualitative criteria such as “combat readiness” and “logistical vulnerability” [1].

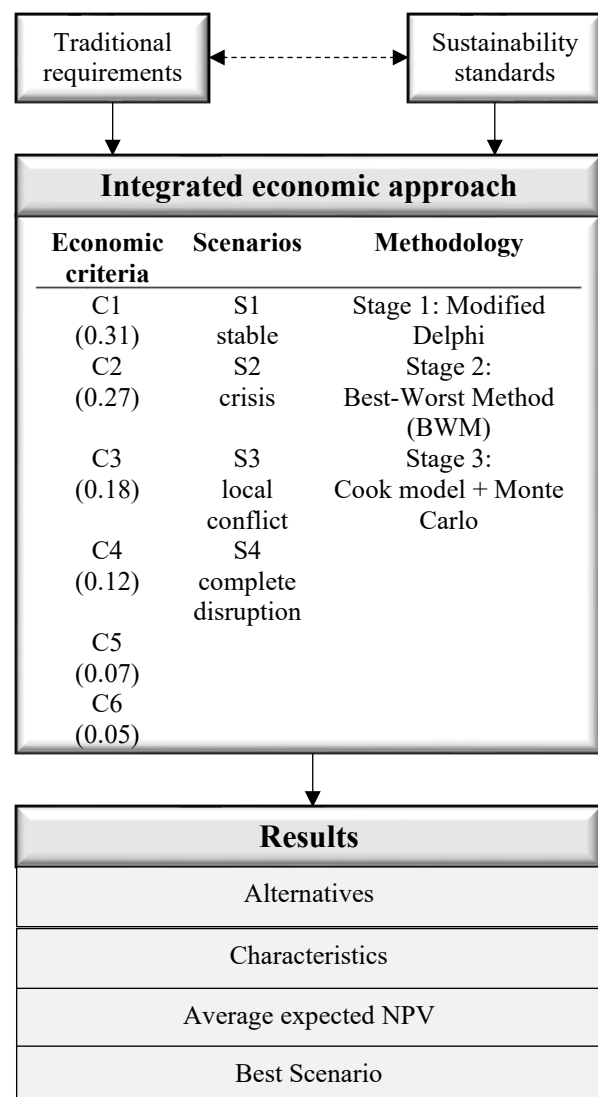


Fig. 1. Conceptual framework for integrating green building into national defense systems - conflict of requirements and bridge via economic criteria (Source: authors' own research).

A. Stage 1: Modified Delphi Method

The modified Delphi method, whose foundations were laid at the RAND Corporation [14], was applied to structure the economic criteria for evaluating green measures at a military base. The method proceeds through three anonymous rounds of surveying, with the interquartile range serving as a quantitative measure of consensus [15]. In the first round, experts freely indicate the criteria and technologies. In the second round, they rate each criterion on a Likert scale from 1 to 5. In the third round, criteria with an interquartile range (IQR) above 0.7 are returned for re-evaluation. Consensus is calculated as (1):

$$Consensus_j = 1 - \frac{IQR_j}{Q_{3j} - Q_{1j}} \quad (1)$$

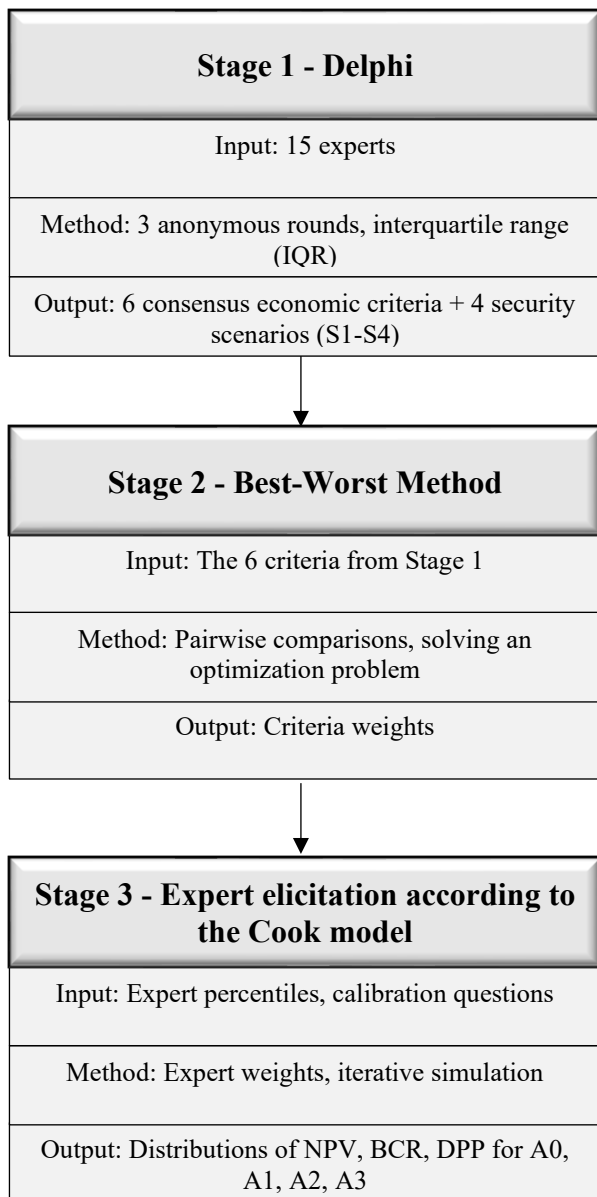


Fig. 2. Integrated methodology based on expert assessments for the defense sector (Source: authors' own research).

and is accepted at a value ≥ 0.7 . This approach has been proven to be reliable in the absence of empirical data [17]. The result of the stage is a list of 6 economic criteria and four security scenarios (stable environment, crisis, local conflict, complete disruption of supplies).

B. Stage 2: Best-Worst Method (BWM)

The Best-Worst Method (BWM) developed by Rezaei [18] was used to determine the weights of the criteria. BWM requires significantly fewer comparisons than AHP and leads to higher consistency [19]. Each expert selects the most important and least important criterion, then rates their preferences on a scale of 1-9. By solving the optimization problem (2):

$$\begin{aligned} \min \quad & \xi \quad (2) \\ \text{under condition:} \quad & \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \quad \forall j \\ & \left| \frac{w_B}{w_W} - a_{jW} \right| \leq \xi, \quad \forall j \\ & \sum_{j=1}^n w_j = 1, w_j \geq 0 \end{aligned}$$

the weights are obtained w_j . Consistency is checked by the CR coefficient, assuming $CR < 0.1$ [20]. Group weights are aggregated by the geometric mean of the individual ratings.

C. Stage 3: Expert elicitation according to the Cook model

Since many parameters (probability of PV failure in an explosion, additional maintenance costs, savings from reducing convoys) cannot be found in the literature, the classic Cook model for expert elicitation [16] is applied. The model is based on objective calibration of experts [23]. Each expert provides the 5th, 50th and 95th percentiles for 10 parameters, as well as answers to 2–3 seed questions, the correct values of which are known to the researchers. For each expert k , calibrations are calculated Cal_k and informativeness Inf_k , and its weight is (3):

$$w_k = \frac{Cal_k \times Inf_k}{\sum_{i=1}^K Cal_i \times Inf_i} \pi r^2 \quad (3)$$

The final distribution of the parameter θ is a mixture of the individual distributions: $f(\theta) = \sum_{k=1}^K w_k f_k(\theta)$. This approach has been successfully applied in engineering and risk analyses. [24].

Monte Carlo Simulation and Economic Model

With the weights and distributions obtained, a Monte Carlo simulation is performed with 1,000 iterations for each alternative (baseline, energy efficiency, hybrid, net-zero) [22]. In each iteration, the net present value (NPV) is calculated (4):

$$NPV = \sum_{t=0}^T \frac{B_t - C_t}{(1+r)^t} \quad (4)$$

where $T = 30$ years, r - discount rate, B_t - benefits (savings of energy, water, fuel, reduced logistical risk), C_t - costs (investment, maintenance, operational). Additionally, the benefit-cost ratio (BCR) and the discounted payback period (DPP) are calculated [21].

Validation is performed by cross-validation of the expert panel (division into two groups, correlation requirement $r > 0.85$ [8]. The permissible deviation is up to 30%.

III. RESULTS AND DISCUSSION

This section presents the results of the three-stage methodology. The expert panel consists of 15 people. Analyses were performed using 1,000 iterations of the Monte Carlo simulation.

A. Results of the Delphi method

After three rounds of the modified Delphi method, consensus was reached ($\text{Consensus}_j \geq 0.70$) for 6 economic criteria, which are presented in Table 1. The criteria are ranked by the median importance score on the 5-point scale.

TABLE 1 CONSENSUS ECONOMIC CRITERIA

Code	Criterion	Median (1–5)	Consensus $_j$
C1	Investment costs (€/m ²)	5.0	0.92
C2	Annual energy savings (€/year)	4.8	0.88
C3	Reduction of logistics convoys (number/year)	4.5	0.85
C4	Annual maintenance costs (€/year)	4.2	0.79
C5	Water savings (€/year)	3.9	0.74
C6	Payback period (years)	3.7	0.71

Source: Authors' own research.

Criteria C1 (investment costs) and C2 (energy savings) receive the highest consensus, confirming that economic efficiency is a top priority in the military sector. The four security scenarios are defined as follows:

S1 (Stable Environment): Normal fuel prices, low risk to convoys.

S2 (Crisis): Fuel prices +50%, moderate risk.

S3 (Local Conflict): Prices +100%, high risk, partial supply disruption.

S4 (Complete disruption): Lack of external fuel and electricity supplies for ≥ 14 days.

B. BWM Results

After applying the Best-Worst Method, the group weights of the six criteria were calculated (Table 2). The value of the consistency coefficient for all experts is $CR < 0.08$, which is below the acceptable threshold of 0.1.

As can be seen, the highest weights are given to investment costs (0.31) and energy savings (0.27), reflecting the typical military focus on initial budget and operational efficiency. Interestingly, the criterion "Reduction of convoys" is given a weight of 0.18, confirming the importance of logistical vulnerability as an economic factor.

C. Results of expert elicitation using the Cook model

Table 3 presents the pooled distributions of three key uncertain parameters obtained after weighting the experts according to their calibration and informativeness. The seed questions show that the average accuracy of the experts' 90% confidence intervals is 82%, which is comparable to published values for engineering applications.

TABLE 2 CRITERIA WEIGHTS OBTAINED THROUGH BWM

Criterion	Weight (w_j)	Standard Deviation
C1 (Investment costs)	0.31	0.05
C2 (Energy savings)	0.27	0.04
C3 (Reduction of logistics convoys)	0.18	0.06
C4 (Maintenance costs)	0.12	0.03
C5 (Water savings)	0.07	0.02
C6 (Payback period)	0.05	0.02

Source: Authors' own research.

These distributions were used as input data for the Monte Carlo simulation.

D. Monte Carlo simulation

Four alternatives for a typical military base were considered:

A0 (Baseline scenario): No green measures, only conventional construction.

A1 (Energy efficiency): LED lighting, thermal insulation, energy-efficient windows.

A2 (Hybrid): A1 + photovoltaics (200 kWp) without batteries.

A3 (Net-Zero): A1 + photovoltaics (300 kWp) + batteries (500 kWh).

After 1,000 iterations, the distributions of the net present value (NPV) for each alternative at a discount rate

of $r = 5\%$ [11] and a horizon of 30 years were obtained. The results are summarized in Table 4.

The highest expected NPV is for alternative A2 (hybrid) - 2.5 million euros, but it also carries higher uncertainty (standard deviation 0.8 million euros). Alternative A1 (energy efficiency only) has the highest probability of a positive NPV (0.96) and the shortest discounted payback period (4.2 years).

E. Analysis of security scenarios

The application of the four security scenarios (S1–S4) significantly changes the economic attractiveness of the alternatives (Table 5). In a stable environment (S1), alternative A1 dominates. In a crisis and local conflict (S2, S3), alternative A2 (hybrid) gives the highest NPV thanks to the reduction of dependence on expensive and risky fuel. In a complete disruption scenario (S4), only alternative A3 (Net-Zero) provides a positive NPV, as it allows for full energy autonomy.

TABLE 3 POOLED EXPERT DISTRIBUTIONS FOR SELECTED PARAMETERS

Parameter (unit)	Distribution type	Parameters
Additional investment costs for PV + batteries (€/kWp)	Triangular	min = 1200, mode = 1800, max = 2500
Probability of PV failure in a near-miss (0–1)	Beta	$\alpha = 2.5$, $\beta = 7.5$ (average 0.25)
Diesel savings from 100 kWp PV (l/yr)	Normal	$\mu = 22\,000$, $\sigma = 4\,500$
Additional annual maintenance of green roofs (€/m ²)	Lognormal	$\mu_{\log} = 1.2$, $\sigma_{\log} = 0.4$

Source: Authors' own research.

TABLE 4 ECONOMIC INDICATORS OF THE ALTERNATIVES (MEAN VALUES $\pm$ STANDARD DEVIATION)

Alternative	Expected NPV	P (NPV > 0)	BCR	DPP (years)
A0	0 (reference)	-	-	-
A1	+1.2 $\pm$ 0.3	0.96	2.1	4.2
A2	+2.5 $\pm$ 0.8	0.89	1.8	6.5
A3	+1.8 $\pm$ 1.1	0.74	1.3	10.2

Source: Authors' own research.

TABLE 5 EXPECTED NPV (€ MILLION) OF ALTERNATIVES UNDER DIFFERENT SECURITY SCENARIOS

Scenario	A1	A2	A3
S1 (stable)	1.5	1.8	0.9
S2 (crisis)	1.2	2.6	1.8
S3 (local conflict)	0.4	3.1	2.5
S4 (complete disruption)	-0.8	0.5	2.2

Source: Authors' own research.

These results show that the hybrid alternative (energy efficiency + RES without batteries) is the most resilient in moderate crises, while Net-Zero is justified only in extreme scenarios of complete isolation.

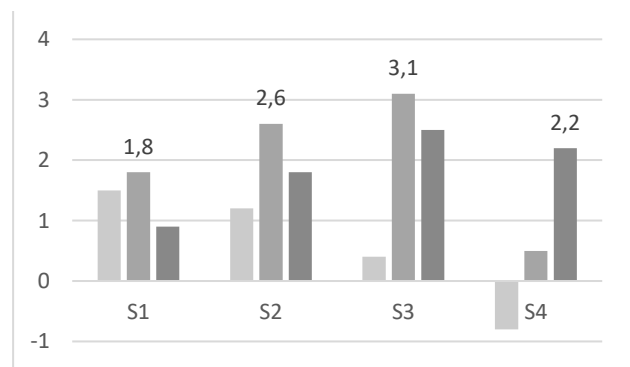


Fig. 3. Comparison of expected Net Present Value (NPV) of three green alternatives under four security scenarios (Source: authors' own research).

Figure 3 shows the expected net present value (NPV) of the three alternatives under four security scenarios. In a stable environment (S1), all three alternatives are positive, with A2 (hybrid) giving the highest NPV. In a crisis (S2) and local conflict (S3), the advantage of A2 becomes sharply pronounced. In a scenario of complete supply disruption (S4), only A3 (Net-Zero) remains positive, while A1 becomes negative. This confirms that the hybrid approach is most resilient in moderate crises, while Net-Zero is justified only in extreme isolation.

Cross-validation with the expert panel divided into two groups shows a correlation of weights $r = 0.89$ ($p < 0.001$), which exceeds the threshold of 0.85. Comparison with published data from the NATO base in Geilenkirchen shows an average deviation of expert cost estimates of 22%, which is below the permissible 30%.

IV. CONCLUSIONS

This study developed and applied a three-stage methodology based on expert assessments (modified Delphi, Best-Worst Method and Cook's model) to economically justify the integration of green building principles in defense infrastructure. The main conclusions are as follows:

a) The economic criteria with the highest priority in the military sector are investment costs and energy savings, followed by the reduction of logistics convoys (weights 0.31; 0.27; 0.18, respectively). This confirms that the focus is on budgetary efficiency and operational autonomy, and not on environmental indicators per se.

b) The hybrid alternative (energy efficiency + photovoltaics without batteries) gives the highest expected net present value (NPV = €2.5 million) and is the most resilient in crisis and local conflict scenarios. In a stable environment, energy efficiency alone (A1) is most advantageous, while Net-Zero (A3) is justified only in a scenario of complete disruption of external supplies.

c) The expert approach is confirmed as reliable in the absence of market data - cross-validation shows a correlation $r = 0.89$, and comparison with real data from a NATO base gives an average deviation of 22% (<30% acceptable).

V. OTHER RECOMMENDATIONS

Recommendations could also be made regarding green building policies in national defense systems through economically sound solutions in the following areas:

a) Military departments should introduce life cycle analysis (LCCA) when approving infrastructure projects to take into account the long-term savings from reduced fuel supplies.

b) Launch pilot projects for hybrid bases (energy efficiency + photovoltaics) in existing military facilities in temperate climates.

c) When justifying security budgets, include scenarios of complete energy disruption as an argument for investments in Net-Zero technologies.

The results obtained depend on the composition of the expert panel and do not take into account the specifics of individual geographical locations. Future research should expand the panel with international experts and verify the model using real data from implemented green systems on military bases.

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