Sustainable Cybersecurity

Jordan Doyle

Integrating Sustainability into Cybersecurity: Insights from Machine Learning Based Topic Modeling

Krishnashree Achuthan, Sriram Sankaran, Rwapnoneel Roy, Raghu Raman

[1]

Discover Sustainability

Research

Integrating sustainability into cybersecurity: insights from machine learning based topic modeling

Krishnashree Achuthan[1] · Sriram Sankaran[1] · Swapnoneel Roy[2] · Raghu Raman[3]

Received: 27 September 2024 / Accepted: 9 December 2024
Published online: 21 January 2025

Abstract
The increasing emphasis on sustainability in computing systems, ranging from small devices to large data centers, is fueled by environmental concerns. Moreover, ensuring cybersecurity in these interconnected networks demands the use of technologies such as resource-intensive cryptography and advanced intrusion detection systems. Our unique study investigates the integration of environmental sustainability into cybersecurity practices by identifying six pivotal themes through a textual analysis of related publications via machine learning based topic modeling. These themes highlight the convergence of cybersecurity with sustainable development goals (SDGs), particularly SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), and 8 (Decent Work and Economic Growth). These include the integration of sustainable cybersecurity measures in smart cities, sustainable digital protection strategies, the application of blockchain for cybersecurity in smart grids, and cybersecurity solutions for SMEs aimed at minimizing resource consumption. Additionally, the study explores multidisciplinary strategies and innovations across four perspectives: adaptive frameworks that prioritize resilience and environmental consciousness, policy shifts for coordinated protection, the power of AI in intelligent threat detection, and the impact of emerging technologies on both security and environmental efficiency. These strategies advocate for an evolved approach that incorporates advanced technologies such as AI, IoT, and blockchain into resilient, sustainable cybersecurity frameworks. This study not only provides a comprehensive overview of the intersection of cybersecurity and sustainability but also serves as a guide for future research and practical applications in creating robust, environmentally friendly cybersecurity practices.

Article highlights

- Explores sustainable cybersecurity aligned with SDGs 7, 8, and 9 using machine learning topic modeling.
- Highlights blockchain, AI, and IoT in cybersecurity for smart grids, SMEs, and resource-efficient systems.
- Advocates adaptive frameworks, AI-driven threat detection, and policy shifts for eco-conscious security solutions.

Keywords Sustainable development goal · Sustainable cybersecurity · Green cybersecurity · Digital economy · Smart city · Smart grids · Machine learning

“The concept of sustainable cybersecurity practices encapsulates a holistic approach to addressing cybersecurity challenges that not only focuses on **immediate threat mitigation** but also considers **long-term impacts on society, the environment, and technological advancement.**” [1]

Achuthan et al.

United Nations Sustainable Development Goals

Picture Source: [3]

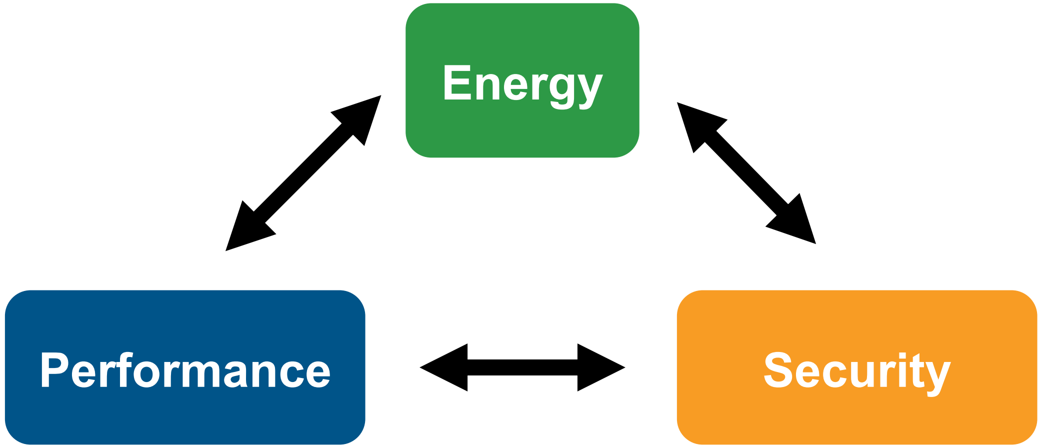
- “The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity.” [2]
- 17 interconnected goals that strive towards worldwide progress

SDGs Mentioned

Picture Source: [3]

Background

- Cybersecurity takes intensive resources
- Cybersecurity is needed to prevent against attacks
  - Cybercrime cost $10.5 trillion by 2025
  - Cybersecurity threats can disrupt daily life in smart cities

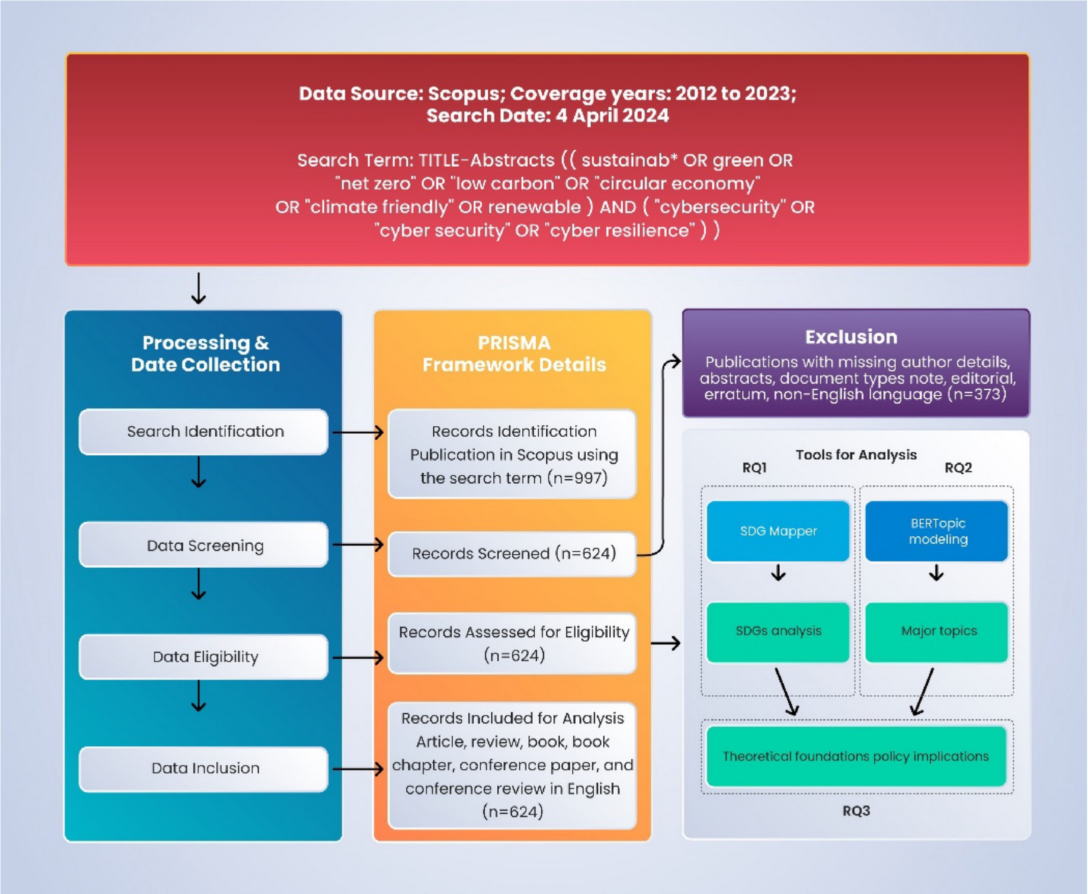


Why is sustainability a challenge in cybersecurity?

- Requires advanced tools (firewalls, IDS, encryption, etc.)
- Adapt rapidly
- Regulatory frameworks
- Protecting robust data
- Proactive risk management
- Budget constraints
- Interconnectivity makes propagation easier
- Scalability challenges

Methods

- April 4th, 2024
- Scopus Database
- 997 publications -> 624
- BERTopic for topic modeling
  - Analyzes text (capturing contextual information) to extract and align topics while using probability analysis to enhance results
- SDG Mapper for creating bubble chart
  - Uses ML and NLP to map research with SDGs

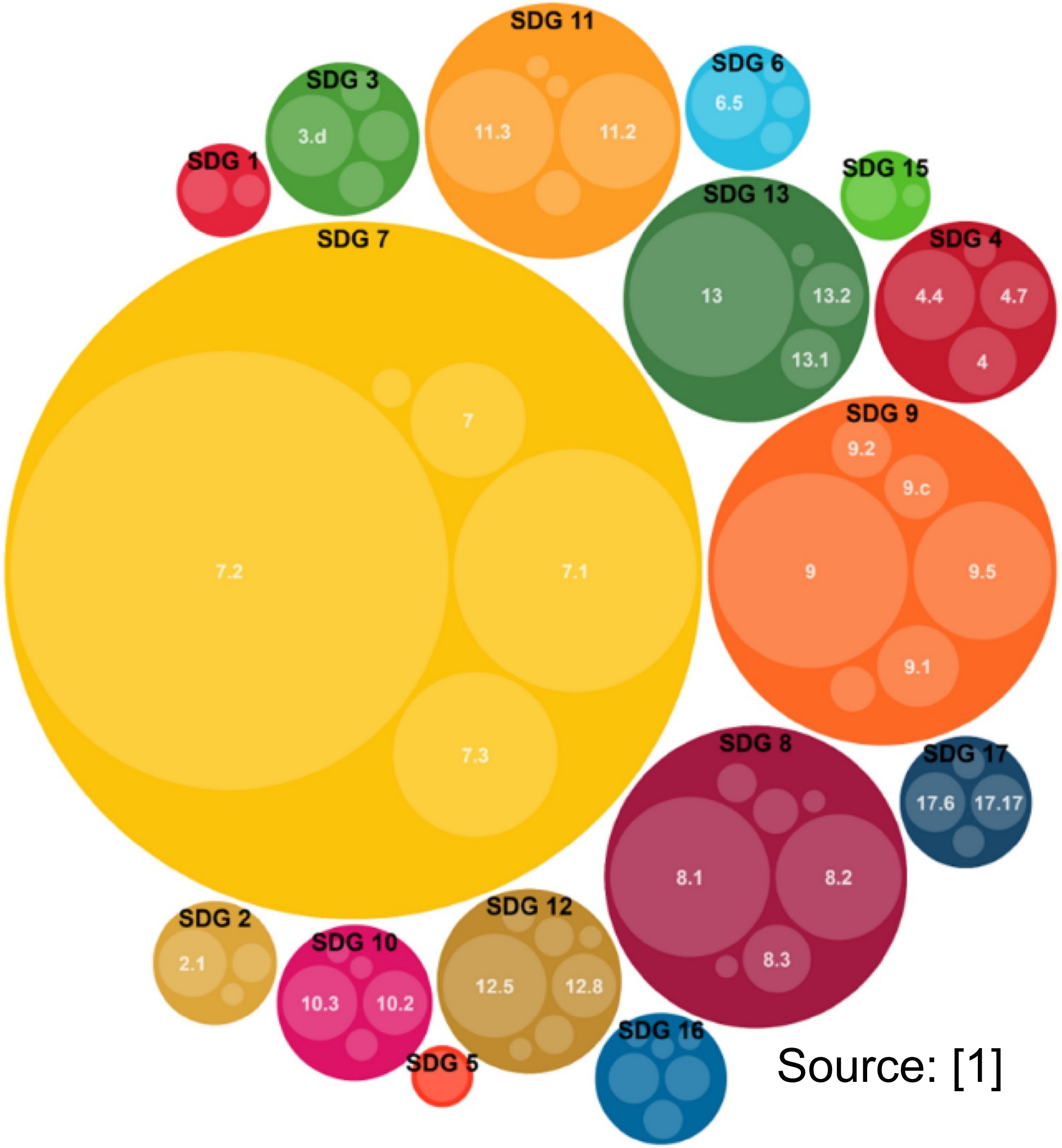


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99

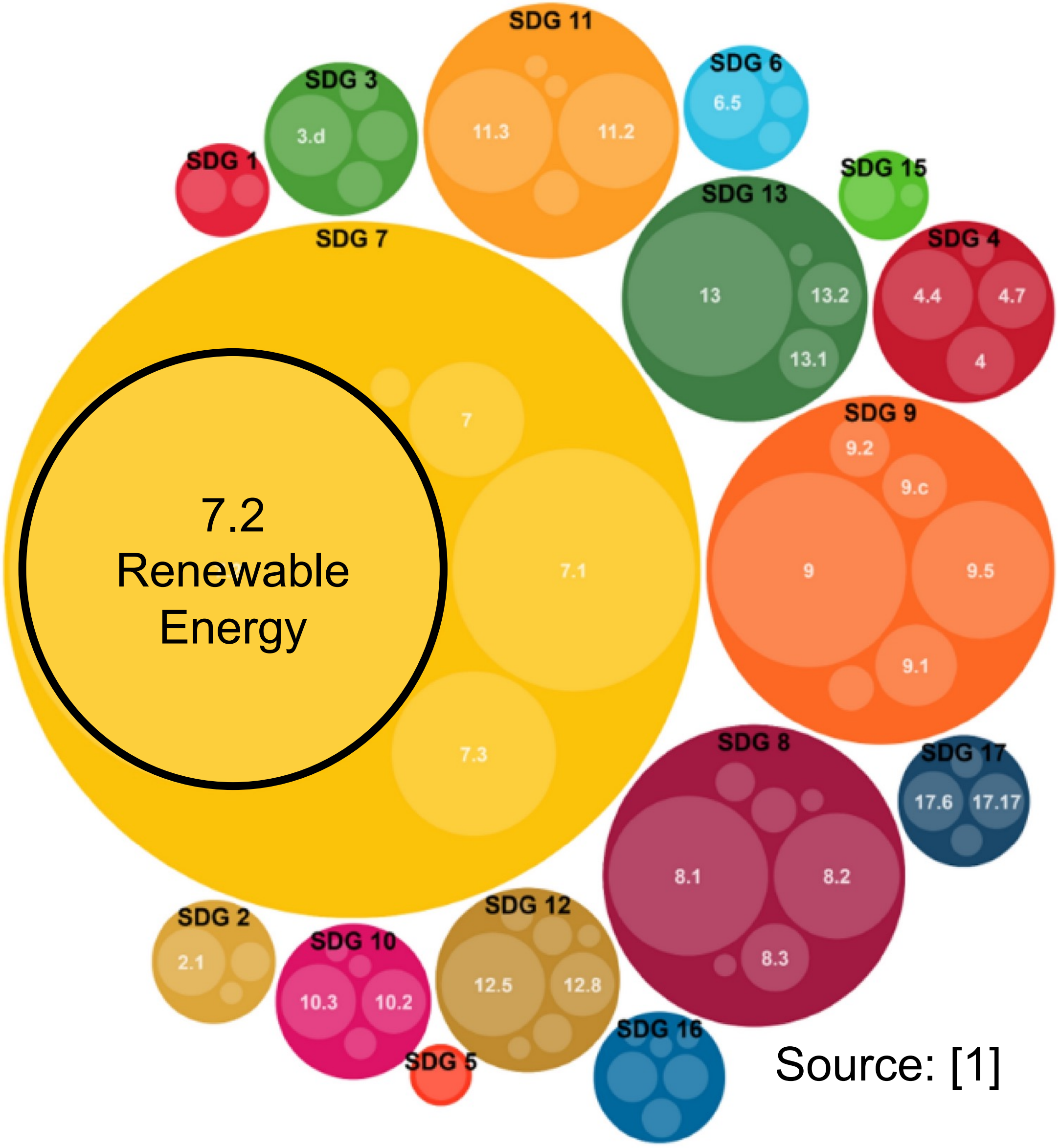


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99

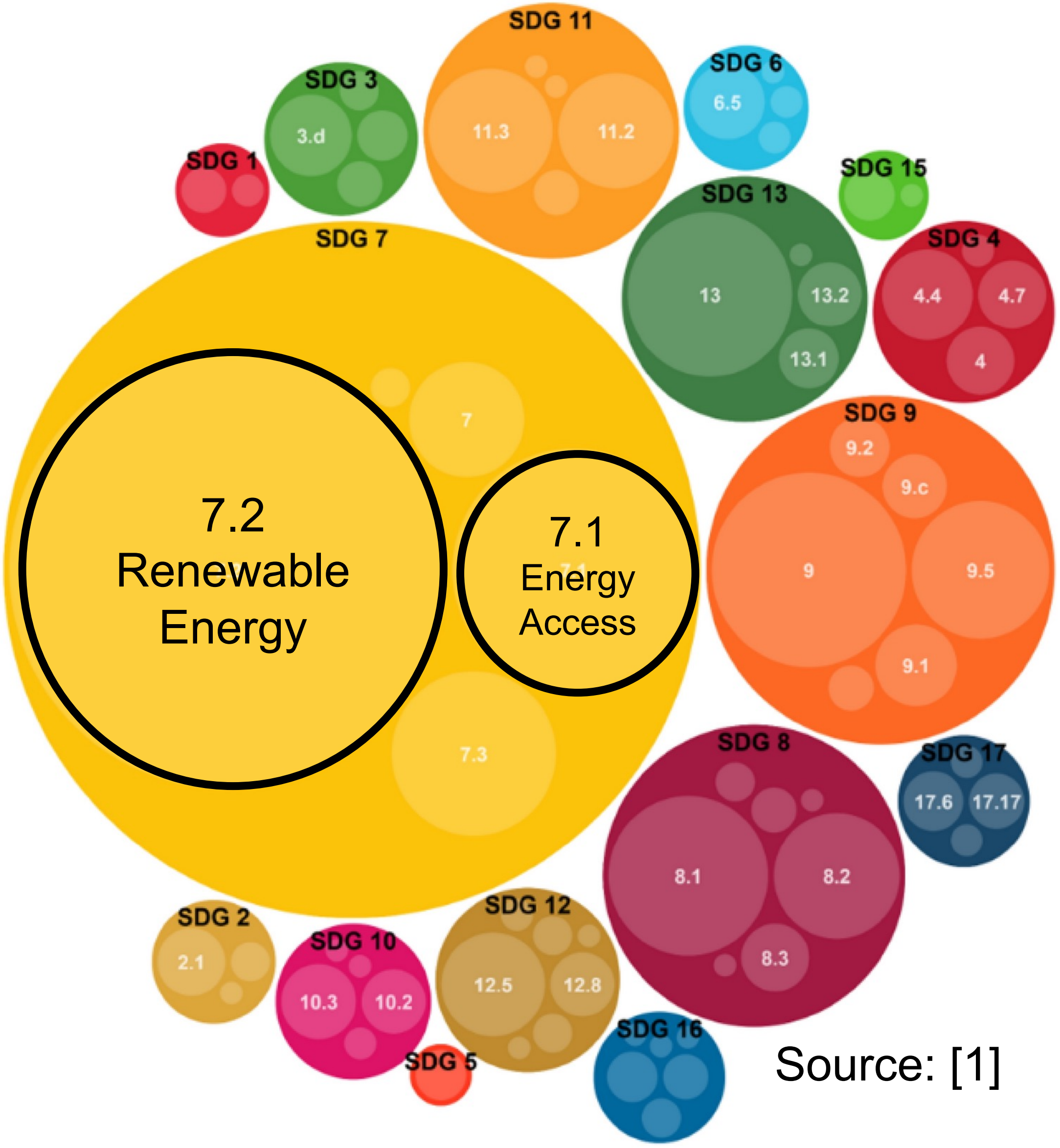


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99

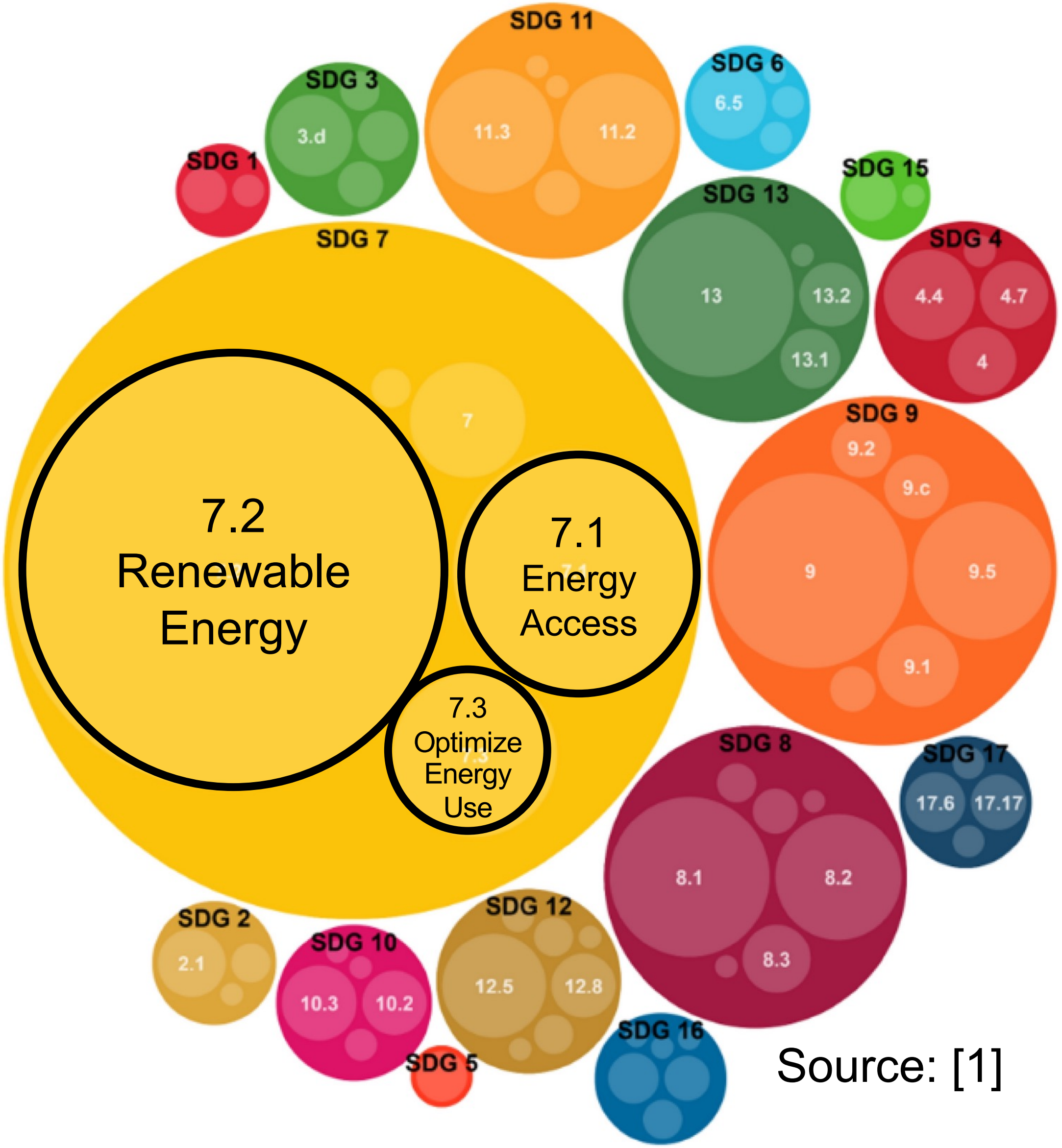


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99

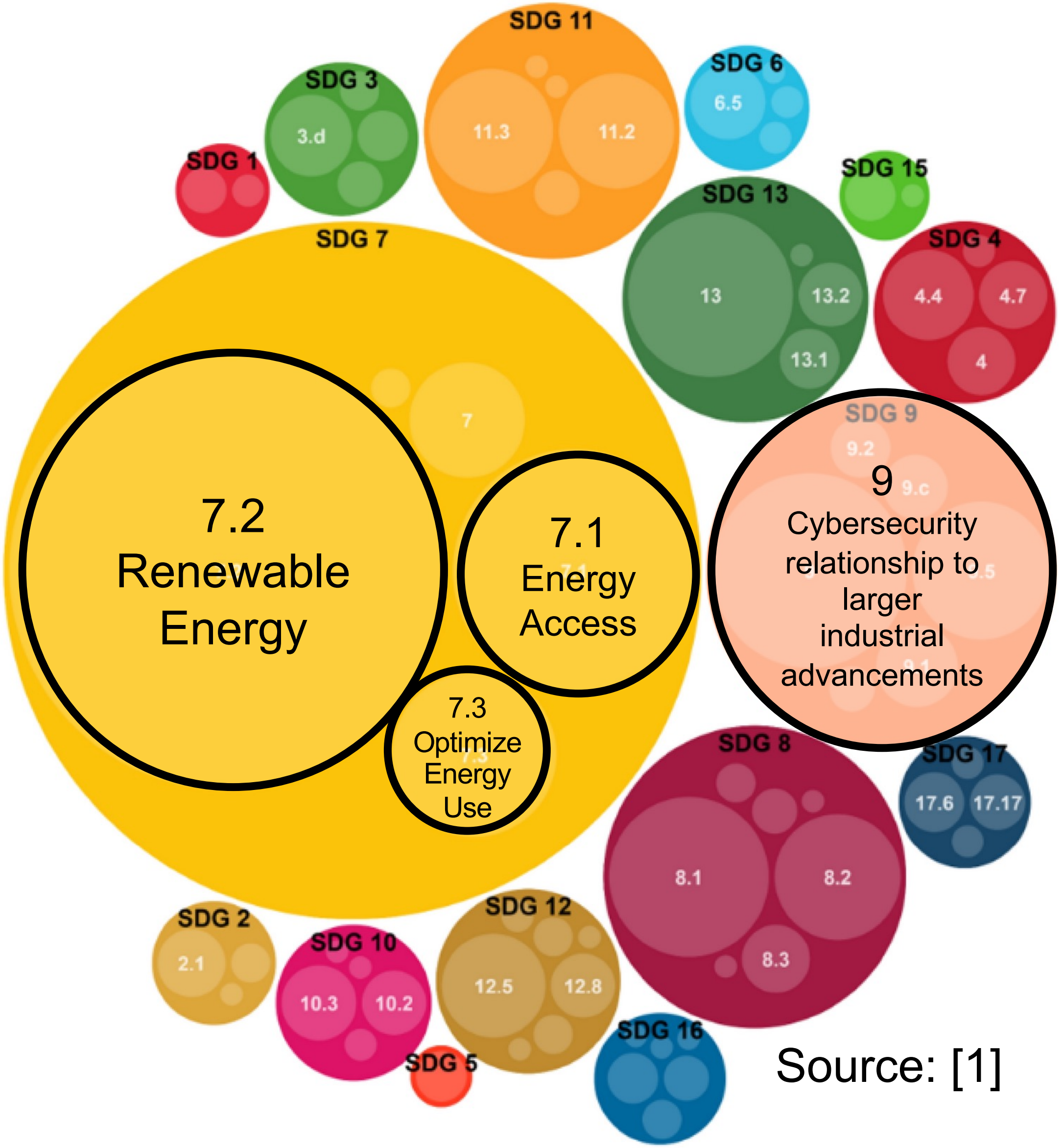


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99

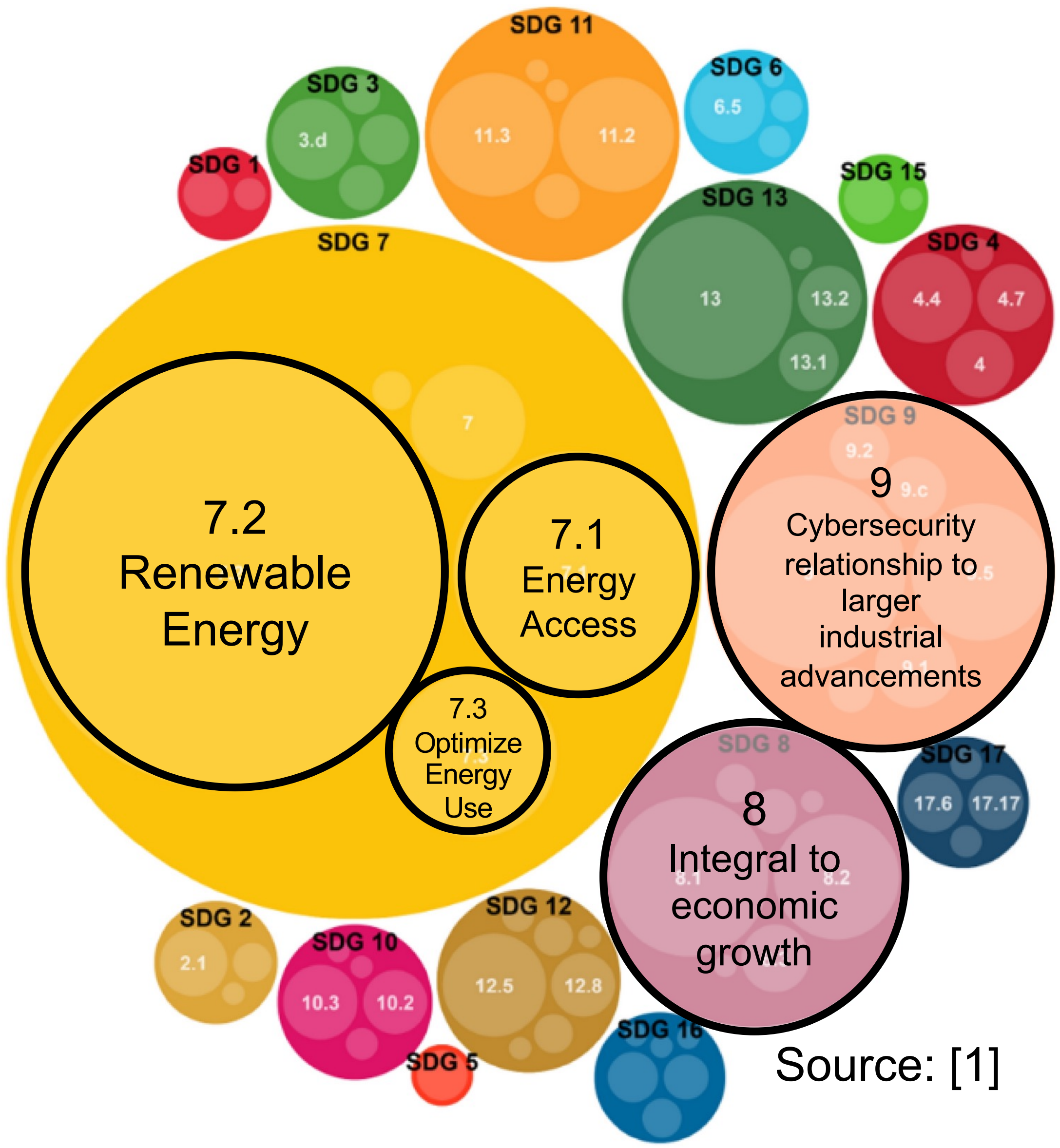


Source: [1]

SDG Mapping

- 169 available targets -> 70 identified

SDG	Focus	Keyword Occurrences
7	Affordable and Clean Energy	572
9	Industry, Innovation, and Infrastructure	143
8	Decent Work and Economic Growth	99



Source: [1]

BERTopic Modeling Themes

Intersection of Cybersecurity and Sustainability

Blockchain Evolution for Sustainable Cybersecurity

Key Sustainability Principles

- Energy efficiency
- Resilience

Key Cybersecurity Concepts

- Decentralization
    - Reducing reliance on energy intensive data centers
- Data integrity
- Fault tolerance
- Resource control

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

13 CLIMATE ACTION

16 PEACE, JUSTICE AND STRONG INSTITUTIONS

Blockchain Evolution for Sustainable Cybersecurity

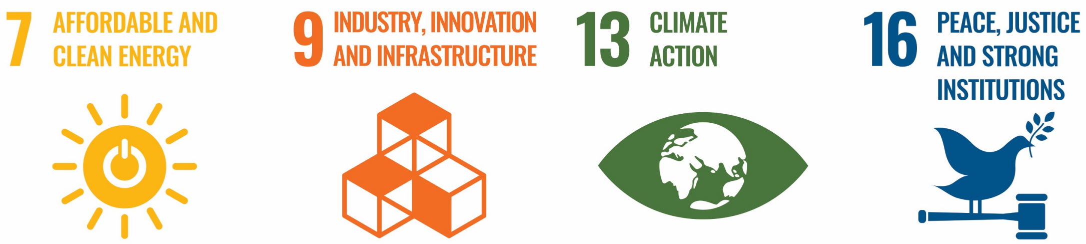
Blockchain: decentralized and distributed digital ledger used to record transactions [4]

Key Sustainability Principles

- Energy efficiency
- Resilience

Key Cybersecurity Concepts

- Decentralization
  - Reducing reliance on energy intensive data centers
- Data integrity
- Fault tolerance
- Resource control



Blockchain Evolution for Sustainable Cybersecurity

Blockchain: decentralized and distributed digital ledger used to record transactions [4]

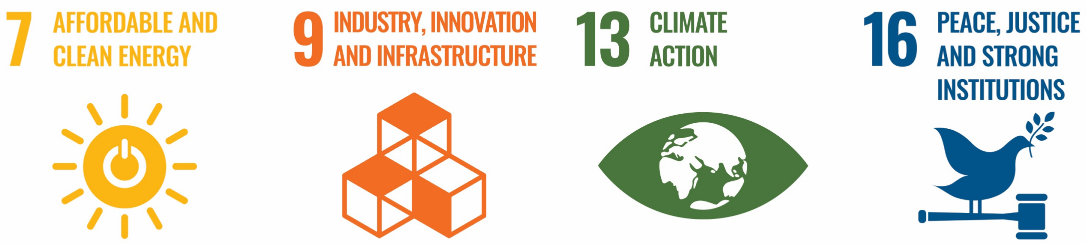
Key Sustainability Principles

- Energy efficiency
- Resilience

Blockchain connection to cybersecurity [5]:
IoT Authentication
Decentralized network for data integrity
Data privacy

Key Cybersecurity Concepts

- Decentralization
  - Reducing reliance on energy intensive data centers
- Data integrity
- Fault tolerance
- Resource control



Green Cybersecurity for Smart City Development

Key Sustainability Principles

- Low-power IoT
- AI optimization
  - Optimizing energy use and transportation
- Energy-efficient data centers

Key Cybersecurity Concepts

- Adaptable security frameworks
- AI & IoT security
- Privacy protection

11 SUSTAINABLE CITIES AND COMMUNITIES

Green Cybersecurity for Smart City Development

Key Sustainability Principles

- Low-power IoT
- AI optimization
  - Optimizing energy use and transportation
- Energy-efficient data centers

Key Cybersecurity Concepts

- Adaptable security frameworks
- AI & IoT security
- Privacy protection

Using technology to optimize resources within a smart city while protecting against vulnerability

11 SUSTAINABLE CITIES AND COMMUNITIES

Integrating Sustainability into Digital Protection

Key Sustainability Principles

- Energy-efficient ML models
- Sustainable intrusion detection

Key Cybersecurity Concepts

- Resilience
- Threat detection
- Intrusion detection
  - Using ML techniques that can more efficiently process large datasets

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Integrating Sustainability into Digital Protection

Key Sustainability Principles

- Energy-efficient ML models
- Sustainable intrusion detection

Key Cybersecurity Concepts

- Resilience
- Threat detection
- Intrusion detection
  - Using ML techniques that can more efficiently process large datasets

9.4: upgrade infrastructure to increase resource-use efficiency

12.2: sustainable management and efficient use of natural resources

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Securing Energy in Space and Renewables

Key Sustainability Principles

- Energy-efficient technologies
- AI for climate resilience

Key Cybersecurity Concepts

- Cyber-resilience
- AI in threat detection
- Securing critical infrastructure
  - Need to protect renewable energy systems to reap their benefits

7 AFFORDABLE AND CLEAN ENERGY

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

Securing Energy in Space and Renewables

Key Sustainability Principles

- Energy-efficient technologies
- AI for climate resilience

Key Cybersecurity Concepts

- Cyber-resilience
- AI in threat detection
- Securing critical infrastructure
  - Need to protect renewable energy systems to reap their benefits

Securing space technologies is key to resiliency in fighting against climate change

7 AFFORDABLE AND CLEAN ENERGY

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

13 CLIMATE ACTION

Sustainable Cybersecurity in Smart Grids

Key Sustainability Principles

- Renewable energy integration
- Energy optimization

Key Cybersecurity Concepts

- Cryptographic chips
- Dynamic security
  - Field programmable gate arrays
- Resilient infrastructure protection
  - Less disruption during cyberattacks

4 QUALITY EDUCATION

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Sustainable Cybersecurity in Smart Grids

Smart Grid: Network that uses technologies to monitor and manage the transportation of energy [6]

Key Sustainability Principles

- Renewable energy integration
- Energy optimization

Key Cybersecurity Concepts

- Cryptographic chips
- Dynamic security
  - Field programmable gate arrays
- Resilient infrastructure protection
  - Less disruption during cyberattacks

4 QUALITY EDUCATION

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Sustainable Cybersecurity in Smart Grids

Smart Grid: Network that uses technologies to monitor and manage the transportation of energy [6]

Key Sustainability Principles

- Renewable energy integration
- Energy optimization

Key Cybersecurity Concepts

- Cryptographic chips
- Dynamic security
  - Field programmable gate arrays
- Resilient infrastructure protection
  - Less disruption during cyberattacks

4 times less energy than GPU or CPU architectures [7]!

4 QUALITY EDUCATION

7 AFFORDABLE AND CLEAN ENERGY

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Digital Economy and Cybersecurity

Key Sustainability Principles

- Circular economy
- Resource efficiency

Key Cybersecurity Concepts

- Data security
- AI in healthcare
- Energy-efficient digital systems

3 GOOD HEALTH AND WELL-BEING

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Digital Economy and Cybersecurity

Key Sustainability Principles

- Circular economy
- Resource efficiency

Minimize environmental impacts while protecting digital systems

Key Cybersecurity Concepts

- Data security
- AI in healthcare
- Energy-efficient digital systems

3 GOOD HEALTH AND WELL-BEING

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Digital Economy and Cybersecurity

Key Sustainability Principles

- Circular economy
- Resource efficiency

Minimize environmental impacts while protecting digital systems

Key Cybersecurity Concepts

- Data security
- AI in healthcare
- Energy-efficient digital systems

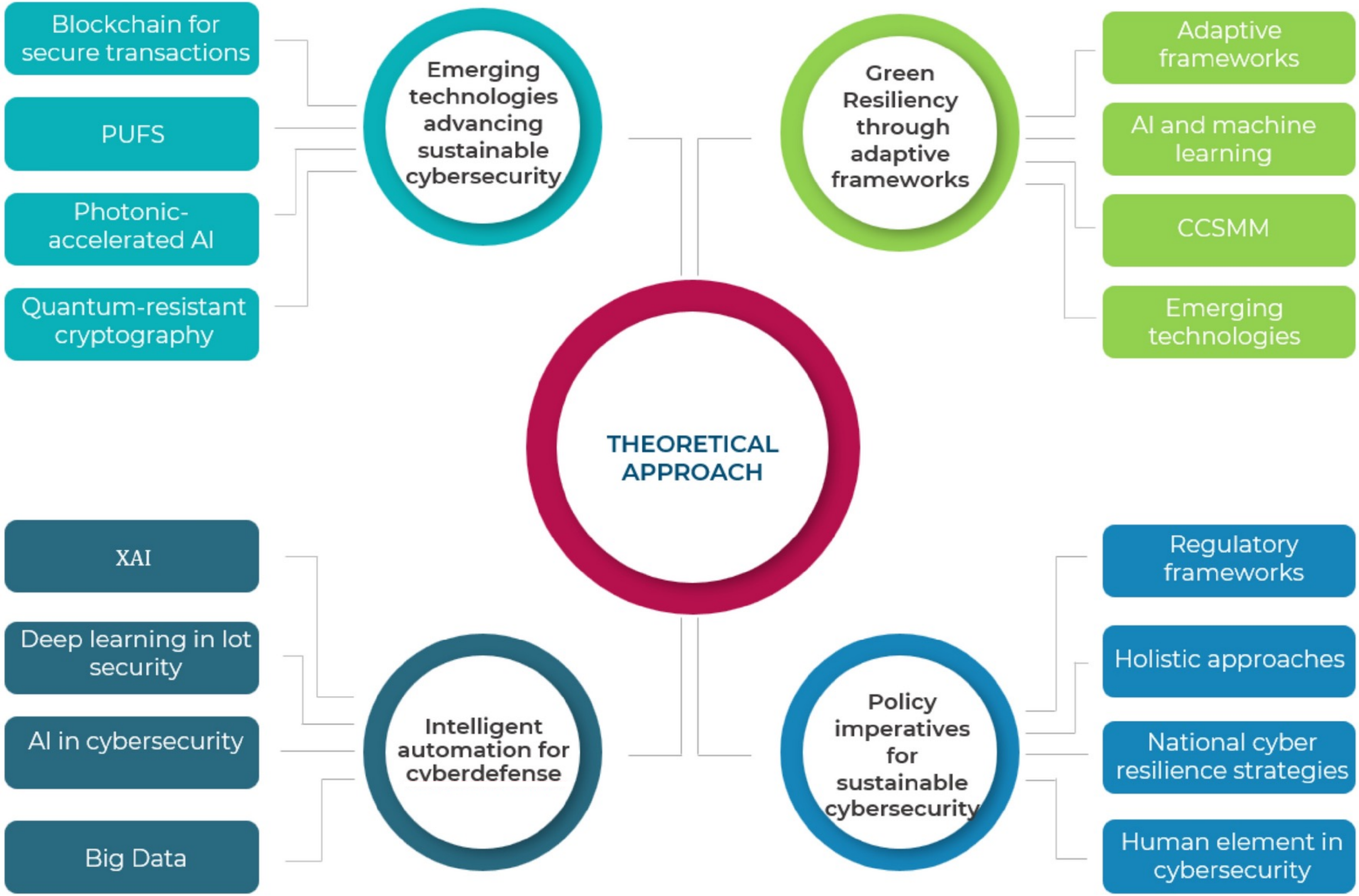
Challenge: ensuring accessibility and innovation without adding environmental strain

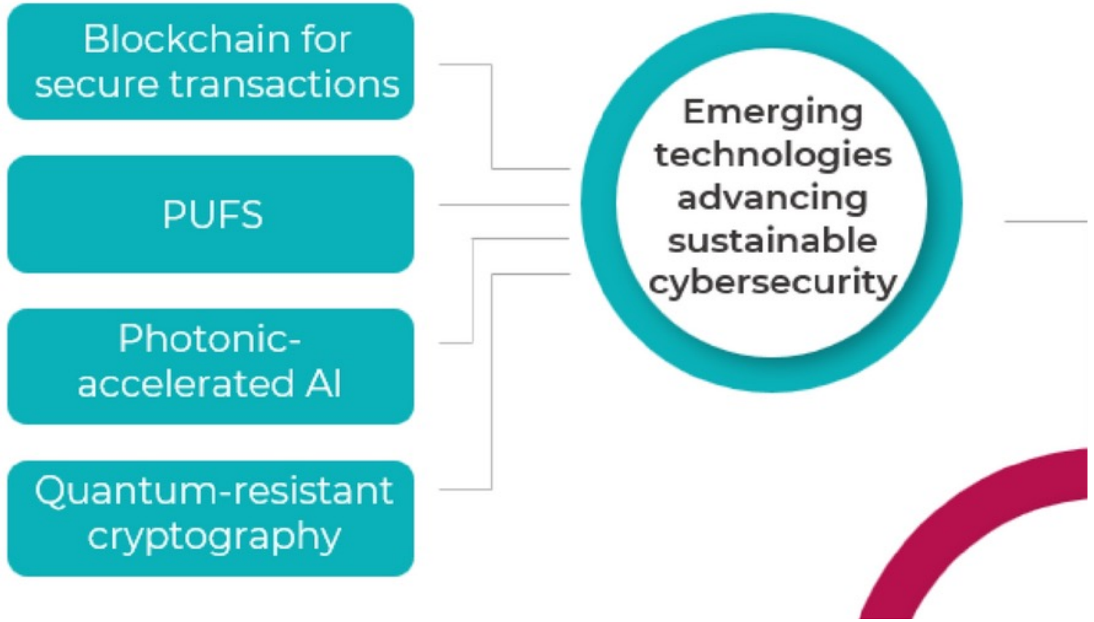
3 GOOD HEALTH AND WELL-BEING

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Theoretical Approaches for the Sustainable Cybersecurity Landscape

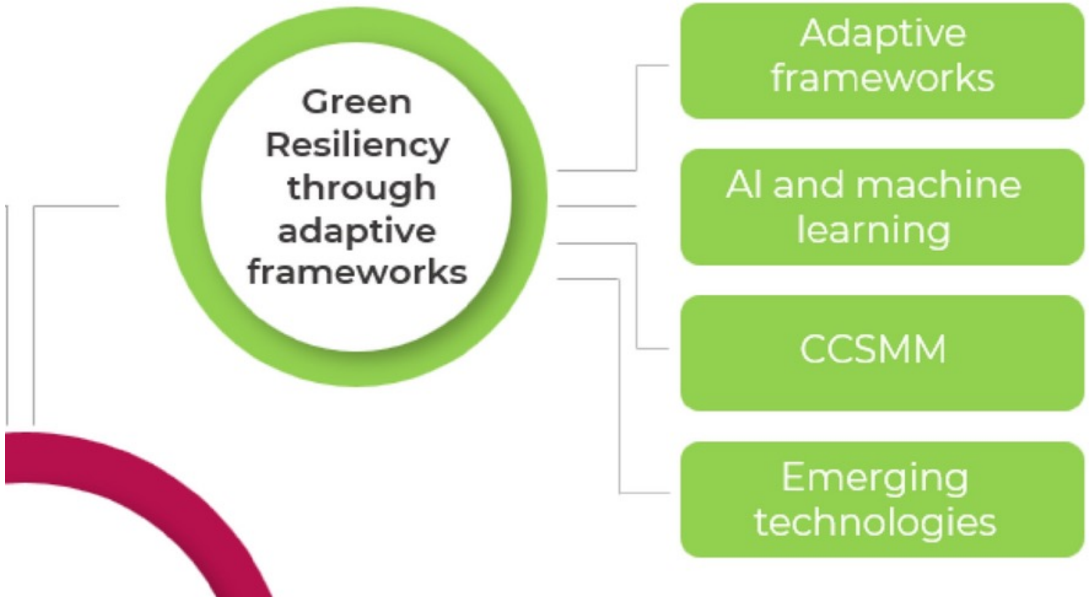
Strategies and innovations to build robust digital defenses


THEORETICAL APPROACH
Emerging technologies advancing sustainable cybersecurity
Blockchain for secure transactions
PUFS
Photonic-accelerated AI
Quantum-resistant cryptography
Green Resiliency through adaptive frameworks
Adaptive frameworks
AI and machine learning
CCSMM
Emerging technologies
Intelligent automation for cvberdefense
XAI
Deep learning in lot security
AI in cybersecurity
Big Data
Policy imperatives for sustainable cybersecurity
Regulatory frameworks
Holistic approaches
National cyber resilience strategies
Human element in cybersecurity



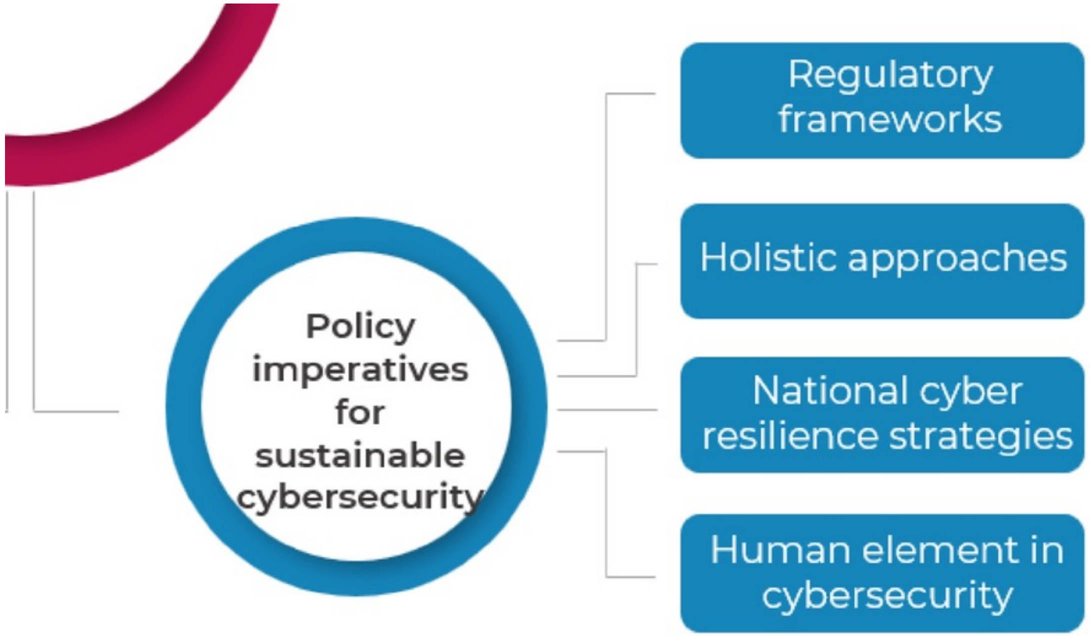
Example: Photonic-accelerated AI

- PIC (Photonic Integrated Circuits) are more energy-efficient and scalable compared to current GPUs
- Utilize Optical Neural Networks (ONN) which have minimal energy loss and work at the speed of light [8]
- Accommodate more AI workloads and solve optimization problems with greater energy-efficiency [9]

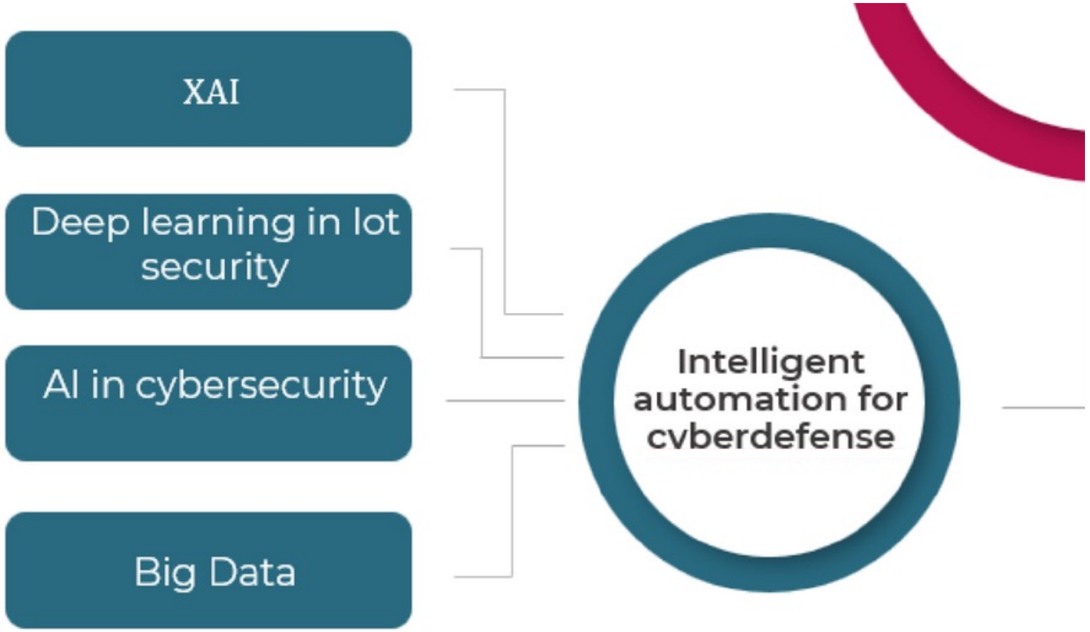


- Need frameworks to embrace emerging technology
  - Ex: zero-trust for IoT systems
- Cybersecurity is a prerequisite to integrating technology solutions into environmental protection strategies
- Comprehensive protocols are needed to safeguard data within smart cities

- Transparency and shared responsibility
  - Building trust to contribute to long-term social and economic stability
- Cybersecurity education
  - Vital for national and international security strategies



- Using AI to address the dynamic threat landscape
- XAI = Explainable AI
  - Transparency builds confidence in AI-decisions which is essential for domains like sustainable development
  - Efficiency -> minimizes resource consumption [10]
- Assessment of systems to ensure robustness while being resource efficient



Implications

Practice

- Optimize existing infrastructure to be more efficient
- Audits of infrastructure
- Innovation
- Modular Software
- Adoption of strategy and education
- Network design

Implications

Practice

- Optimize existing infrastructure to be more efficient
- Audits of infrastructure
- Innovation
- Modular Software
- Adoption of strategy and education
- Network design

Policy

- Creating and enforcing specific environmental criteria
- Guidelines for design
- Tax incentives, grants, subsidies
- Public funding
- Sharing knowledge
- Educational programs

Future Research

- Assessment and alignment with the SDGs
- Policies that encourage green technologies and sustainable practices
- Energy-efficient hardware and software solutions
- Training programs
- Security at design stage of products
- Evaluation and reporting

Key Takeaways

Key Takeaways

1. Cybersecurity is essential to sustainable development, particularly in infrastructure development, economic growth, and renewable energy access

Key Takeaways

1. Cybersecurity is essential to sustainable development, particularly in infrastructure development, economic growth, and renewable energy access

2. Cybersecurity is resource-intensive, but the combination of AI and energy-efficient hardware will reduce the environmental strain

Key Takeaways

1. Cybersecurity is essential to sustainable development, particularly in infrastructure development, economic growth, and renewable energy access

2. Cybersecurity is resource-intensive, but the combination of AI and energy-efficient hardware will reduce the environmental strain

3. There is a growing need for new policies and strategic frameworks that promote both robust cybersecurity and progress towards the United Nations Sustainable Development Goals (SGDs).

Questions?

References

[1] K. Achuthan, S. Sankaran, S. Roy, and R. Raman, “Integrating sustainability into cybersecurity: insights from machine learning based topic modeling,” *Discover Sustainability*, vol. 6, no. 1, Jan. 2025, doi: https://doi.org/10.1007/s43621-024-00754-w.

[2] United Nations Development Programme, “Sustainable Development Goals,” *United Nations Development Programme*, 2024. https://www.undp.org/sustainable-development-goals (accessed Apr. 30, 2025).

[3] United Nations, “Communications materials,” *United Nations Sustainable Development*, 2024. https://www.un.org/sustainabledevelopment/news/communications-material/ (accessed Apr. 30, 2025).

[4] Blackduck, “What Is Blockchain and How Does It Work?,” *Black Duck*, 2023. https://www.blackduck.com/glossary/what-is-blockchain.html (accessed Apr. 30, 2025).

[5] P. J. Taylor, T. Dargahi, A. Dehghantanha, R. M. Parizi, and K.-K. R. Choo, “A systematic literature review of blockchain cyber security,” *Digital Communications and Networks*, vol. 6, no. 2, pp. 147–156, Feb. 2019, doi: https://doi.org/10.1016/j.dcan.2019.01.005.

[6] International Energy Agency, “Smart Grids,” *IEA*, Jul. 11, 2023. https://www.iea.org/energy-system/electricity/smart-grids (accessed Apr. 30, 2025).

[7] Rodríguez-BorbónJ. M., A. Kalantar, S. S. R. K. C. Yamijala, M. B. Oviedo, W. Najjar, and B. M. Wong, “Field Programmable Gate Arrays for Enhancing the Speed and Energy Efficiency of Quantum Dynamics Simulations,” *Journal of Chemical Theory and Computation*, vol. 16, no. 4, pp. 2085–2098, Mar. 2020, doi: https://doi.org/10.1021/acs.jctc.9b01284.

[8] “2025 IEEE Study Leverages Silicon Photonics for Scalable and Sustainable AI Hardware,” *The IEEE Photonics Society*, Apr. 09, 2025. https://ieeephotonics.org/announcements/2025ieee-study-leverages-silicon-photonics-for-scalable-and-sustainable-ai-hardwareapril-3-2025/ (accessed Apr. 30, 2025).

[9] B. Tossoun *et al.*, “Large-Scale Integrated Photonic Device Platform for Energy-Efficient AI/ML Accelerators,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 31, no. 3: AI/ML Integrated Opto-, pp. 1–26, May 2025, doi: https://doi.org/10.1109/jstqe.2025.3527904.

[10] S. S. Infant, S. Vickram, A. Saravanan, C. M. Mathan Muthu, and D. Yuarajan, “Explainable artificial intelligence for sustainable urban water systems engineering,” *Results in Engineering*, vol. 25, p. 104349, Feb. 2025, doi: https://doi.org/10.1016/j.rineng.2025.104349.