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PP-203 [Beekeeping Technology and Quality]

Solar-Powered Smart Hives Network for Beekeeping and Long-Term Research

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Objectives

- Develop autonomous, **solar-powered IoT-based smart hives** capable of year-round operation in regions with long winters, snow, and harsh climates.
- Build a Smart Hives Network capable of continuous multi-year operation, with **a standardized frequency** of digitization and data transmission.
- Create a continuously growing, homogeneous database suitable for machine learning and AI-based colony behavior modeling.
- Design a system for **non-invasive monitoring** to support long-term scientific research and practical beekeeping, with a focus on sustainability, data-driven decision-making, and **early risk prediction**.

Introduction

- The lack of homogeneous, high-quality, and comparable data from beehives limits the application of machine learning (ML) and artificial intelligence (AI) in both honeybee research and precision beekeeping.
- **Without real-time hive data**, beekeepers cannot promptly respond to rapid and critical threats such as autumn or spring **honey robbing**, or **overwintering failure** — for example, dangerously **high humidity inside** the hive during winter — nor can they efficiently optimize logistical and operational efforts.
- Furthermore, traditional monitoring methods are invasive, episodic, and unsuitable for **long-term or winter** analysis.
- The absence of multi-year, standardized datasets from diverse regions makes it difficult to assess the long-term impacts of **climate change** on colony health and behavior.
- This project introduces a solar-powered, field-tested smart hive network that addresses these gaps by enabling autonomous, non-invasive, regularly timed data collection under natural conditions across varied climates in **Europe and North America.**

Materials and Methods

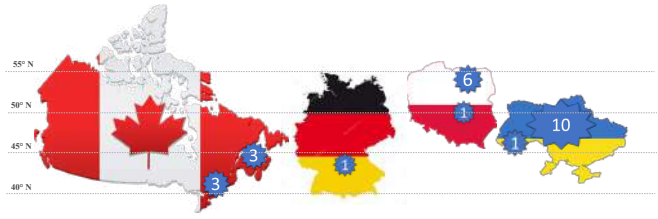
- A standardized network **of ~25 AmoHive smart hives (Langstroth type)** was deployed across multiple regions **(43–54°N latitude)** including Poland, Ukraine, Canada, and Germany.
- Each hive operates autonomously, powered exclusively by solar energy, and is equipped with internal sensors for weight, internal/external temperature, humidity, and solar voltage.
- All devices use **adaptive sleep/wake cycles** based on solar irradiance:
  - In spring/summer — activation occurs hourly;
  - In autumn/winter — activation is reduced to every 2+ hours.
- The smart hives have been operating continuously **since 2019,** even under extreme natural conditions such as **–35 °C** in Canada and prolonged **high humidity** in northern Poland.
- Collected data are wirelessly transmitted and stored in a centralized, growing database, forming **a multi-year, homogeneous time series** suitable for machine learning and AI-based modeling.
- The adaptive activation mode of the IoT system — with time-regular cycles driven by available solar irradiance — aligns with the seasonal dynamics of the colony. This approach ensures long-term **autonomous functionality**, **conserves energy**, and **minimizes interference with the bees' natural behavior**.

Innovation

- A continuously operating smart hive network powered exclusively by solar energy for **over 7 years** — validated across diverse climates in Canada and Europe.
- **Energy-efficient sleep mode** minimizes electromagnetic emissions and prolongs device functionality, reducing potential negative impacts on bee health and behavior.
- **Ultra-low data traffic**: hourly transmission of compact data packets (just a few kB) sufficient for real-time colony assessment and predictive modeling.
- **Mobile application** for intuitive, real-time visualization of key hive metrics, supporting both researchers and beekeepers in field conditions.

Smart Hives Network

Smart hives deployed across a latitudinal range from 43°N (Toronto, Canada) to 54°N (Masuria, Poland)



Smart Hive

Core unit of the network: AmoHive smart hive based on the Langstroth design.
Patent UA133650, 10 April 2019

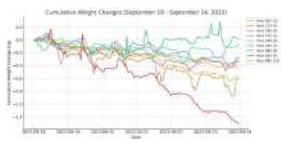
Figure 1. Smart Hive AmoHive

Results

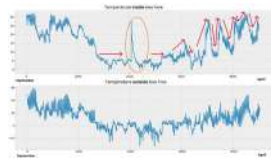
- Over **20,000 days** of monitoring across a standardized network of solar-powered smart hives deployed in Europe and North America, generating nearly **one million synchronized records** of colony behavior and environmental hive conditions.
- The IoT system remained functional under extreme climates: from –35 °C winters in Ontario to high humidity in the Masurian Lake District, operating autonomously year-round.
- A wide range of **cyclic and non-cyclic behavioral patterns** was detected and visualized. In addition to typical daily activity curves (varieties of the *'Breakfast Canyon'*), more complex seasonal and rare patterns were documented.
- Examples include:
  - Honey robbing prediction (spring/autumn)
  - Wintering success and failure patterns
  - **Solar irradiance impact** on nectar flow (e.g., Taraxacum officinale)
  - Colony queenlessness and drone-laying symptoms detection
- **Solar irradiance** values were **calibrated and synchronized** using **real-time panel voltage** and cross-referenced with NASA POWER, Copernicus, and Open-Meteo (by hive **GPS coordinates**).

Pattern: **Honey Robbing**

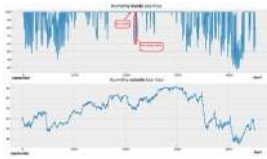
Forecasting:
Prediction horizon: **up to 7 days**
Method: **Weight + Moving Window Anomaly Detector**



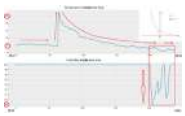
Pattern: **Overwintering, Fondant & Temperature**
Internal temperature dynamics after winter fondant feeding, compared with external temperature conditions.



Pattern: **Overwintering, Fondant & Humidity**
Internal humidity dynamics after winter fondant feeding, compared with external humidity levels.



Pattern: **Overwintering, Fondant (Detailed)**
Fourteen-day dynamics of internal temperature and humidity following winter fondant feeding.



Summary: Fondant, Microclimate, and Spring Forecasting
During overwintering, when internal humidity approaches critical levels (up to 100%), the application of winter fondant improves both colony condition and hive microclimate.
It triggers a sharp internal temperature increase of 10–20 °C, followed by a gradual exponential decline over 7–14 days, accompanied by a decrease in humidity.
The amplitude, duration, and internal/external temperature and humidity differentials provide insight into colony strength and enable forecasting of early spring development. This adaptive response enhances winter survival under cold and humid conditions.

Pattern: **Nectar Flow & Solar Irradiance**
Pattern showing the relationship between nectar collection activity and solar irradiance dynamics.

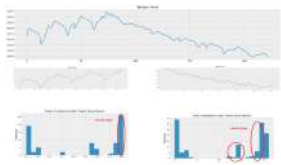


Figure 2. Smart Apiary in Ukraine

Further details on honey robbing prediction are available in the scientific article: Kurdin, I.; Kurdina, A. Internet of Things Smart Beehive Network: Homogeneous Data, Modeling, and Forecasting the Honey Robbing Phenomenon. Inventions 2025, 10(2), 23. https://doi.org/10.3390/inventions10020023

Figure 3. Smart Apiary in Poland

Conclusions

- Multi-year data collected from identical solar-powered smart hives provide a robust foundation for developing **an adaptive predictive model** of honeybee colony dynamics with **integrated anomaly detection**. This model is based on historical and **real-time** hive parameters, **solar irradiance** data, a **library of behavioral patterns**.
- The standardized and time-synchronized dataset is well-suited for ML applications, diagnostics, and early warning systems.
- Digitized, non-invasive overwintering data offer practical value for improving **overwintering practices** in traditional beekeeping.
- **GPS-tagged honey flow records** increase consumer **trust** and help **verify honey** authenticity.
- Solar irradiance data obtained from hive-mounted panels, synchronized with global datasets (e.g., NASA POWER, Copernicus), provide a novel source of information for studying bee orientation, foraging behavior, and activity under natural conditions.

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Scientific research on honeybee colonies in natural conditions increasingly relies on Internet of Things (IoT)-based monitoring systems. These systems enable simultaneous collection of internal and external hive parameters, improving data comparability and research efficiency. High-quality data allow the effective application of machine learning and predictive modeling to mitigate negative developments in honeybee colonies housed in smart hives with IoT-based monitoring. However, these advancements impose higher requirements for data quality, including homogeneity, continuity, standardization, completeness, and consistency. Additionally, IoT devices must operate autonomously under extreme climatic conditions while balancing energy consumption, digitization frequency of hive parameters, and long-term functionality. This study presents a practical, field-validated solution that has operated continuously for several years in harsh European and North American climates. We introduce an innovative smart hives network architecture, where permanently embedded IoT sensors function exclusively on solar energy while collecting high-quality, non-invasive data. The IoT devices remain in sleep mode most of the time, activating based on solar radiation. During periods of high solar availability, typically in spring and summer, the devices activate hourly for a few minutes to collect and transmit data. In autumn and winter, with minimal solar energy, they operate less frequently, usually every two hours. This adaptive cycle corresponds to the seasonal dynamics of honeybee colonies. Continuous non-invasive data collection is particularly valuable for monitoring overwintering colonies, where invasive methods are impractical. Tracking internal hive conditions, regulating humidity, and providing timely winter feeding contribute to successful overwintering and early colony development, essential for pollination, especially in early spring, for agricultural crops. Additionally, solar panel data from each hive serve as a supplementary, non-invasive information source, potentially influencing honeybee behavior during monofloral honey collection. Our continuously operating smart hives network provides high-quality, non-invasive data on honeybee life, enabling advanced long-term research and supporting both traditional and precision beekeeping while addressing sustainability challenges in the context of climate change.