Batteryless Autonomous Water-Leak Prevention

ENF AquaFuse / PipeGuard – Patent Landscape and Engineering Feasibility

Towards a Deterministic Offline Mitigation Device for Cold-Climate European Homes

— **Danish Z. Khan**, Founder, ENFSystems LLC

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Abstract

Domestic water leaks are a rising threat to the financial stability of homeowners and insurers in cold-climate Europe. A press release dated 7 November 2025 reports that burst pipes and leaky fittings generated **€4.9 billion in insured losses in Germany during 2024** and that more than **half of all building-insurance claims** now stem from water damage (Finanztip, 2025). Complementary data from the German Insurance Association show **1.17 million claims in 2021** with an average payout of €3,213 (Maklermagazin, 2022). Existing “smart” shut-off valves tend to be notification-first gadgets that depend on mains electricity, disposable batteries and cloud servers; when storms or freeze events take down power and internet, they leave the home unprotected (Moen Incorporated, 2023). This paper presents **ENF AquaFuse / PipeGuard**, a patent-informed concept for a batteryless, offline mitigation device that integrates a micro-turbine energy harvester, supercapacitor storage, deterministic embedded neural firmware (ENF) and a mechanical spring-loaded fail-safe valve with manual override. A documented search protocol covering Espacenet, WIPO Patentscope, Google Patents, manufacturer manuals and academic literature found **no evidence of any product or patent combining all six resilience criteria** (automatic shutoff, self-powered operation, flow-energy harvesting, supercapacitor storage, offline autonomy and mechanical fail-safe) as of **27 December 2025**. Hydraulic and electrical calculations show that a 10 F, 5 V supercapacitor bank stores roughly 125 joules—sufficient for sensing, inference and multiple actuation attempts—while a bypass micro-turbine can harvest tens to hundreds of milliwatts without exceeding acceptable pressure-drop limits (Li & Chong, 2019). The architecture accounts for EU safety and hygiene regulations including the Pressure Equipment Directive (PED 2014/68/EU) (European Parliament & Council of the European Union, 2014), the German UBA evaluation criteria for drinking-water materials and the General Product Safety Regulation (GPSR 2023/988). Comparative pricing suggests that production costs of €45–70 and retail prices of €149–249 would undercut existing mains-powered devices while eliminating maintenance. The ENF AquaFuse concept thus represents a new class of infrastructure-grade leak-prevention hardware; this paper synthesises the patent landscape, presents a worked feasibility example and proposes a validation plan. For full competitive evidence and search protocol details, see **Appendices A** and **C**.

Keywords: water-leak prevention, energy harvesting, embedded neural firmware, supercapacitor, mechanical fail-safe, EU compliance, cold climate, leak detection, patent landscape, unit economics

1 Introduction

1.1 The water-damage crisis in cold-climate Europe

Water leakage and burst pipes have escalated into the primary driver of property-insurance claims across cold-climate Europe. According to the press release cited above, **burst pipes and leaky fittings caused €4.9 billion in insured losses in Germany in 2024** and accounted for more than **50 % of all building-insurance claims** (Finanztip, 2025). The GDV recorded **1.17 million claims in 2021** with total payouts of €3.81 billion and an average claim size of €3,213 (Maklermagazin, 2022). Water-damage incidents now outnumber those from storm, theft and fire combined; in 2024 they represented **28.6 % of all declared home-insurance claims** (Maklermagazin, 2022). Frost bursts remain a major problem, with tens of thousands of pipe bursts each winter. Given that northern European winters bring extended sub-zero temperatures and ageing plumbing infrastructure, the risk to property owners is only growing.

1.2 Limitations of existing smart-valve solutions

The smart-home market offers numerous connected valves and leak sensors, yet these devices share structural weaknesses:

1. **Dependence on electricity and connectivity.** Leading products such as **Flo by Moen** and **Phyn Plus** require a nearby AC outlet and a stable Wi-Fi connection; Moen's installation manual specifies that the Flo unit must be connected to an AC power outlet and Wi-Fi network (Moen Incorporated, 2023), and Phyn's installation requirements call for a power outlet within 12 feet and Wi-Fi access (Phyn LLC, 2023). When storms or freeze events disrupt power or broadband, these devices cannot detect or isolate leaks.
2. **Notification-first design.** Many devices send a push notification rather than autonomously closing the water line. If occupants are asleep or away, a burst can continue for hours.
3. **Maintenance burden.** Battery-powered systems (e.g., Resideo, AquaTrip) require periodic battery replacement; mains-powered devices demand firmware updates, subscriptions and network troubleshooting. AquaTrip's official product page notes that its wireless control panel is powered by long-life batteries and requires no wiring or Wi-Fi (AquaTrip Pty Ltd., 2023). LeakSmart's installation manual instructs installers to connect the valve to a 9 V AC power supply and recommends installing four AA batteries for backup (LeakSmart, 2021).
4. **Lack of fail-safe closure.** Motor-driven ball valves remain open when power is lost. The Grohe Sense Guard manual notes that the valve stays open during a power outage and requires mains electricity for operation (Grohe AG, 2019); Wi-Fi is necessary for monitoring and remote control but not for the core shut-off function. There is usually no mechanical latch or manual override.

These limitations highlight the need for a mitigation-first, batteryless system that senses anomalies and physically isolates the water supply autonomously, without dependence on mains power, batteries or cloud services.

1.3 Contributions of this paper

This work consolidates a patent analysis and engineering feasibility study into a coherent, publish-ready research paper. Its main contributions are:

1. **Search protocol and competitive gap analysis.** A reproducible patent and product scan is documented to enable auditing of the novelty claim (Appendix C).
2. **System concept definition.** The ENF AquaFuse architecture is described, emphasising offline, deterministic operation, energy harvesting and a spring-latch mechanism with manual override.
3. **Feasibility analysis.** Hydraulic and electrical calculations show that the device can operate within realistic flow and pressure constraints, with a worked example.
4. **Safety and failure handling.** A mini-FMEA and state-machine description articulate how the device maintains a fail-safe state and recovers from faults.
5. **Patent landscape summary.** Related patents are mapped into clusters and the feature gaps that define AquaFuse's novelty are identified.
6. **Unit economics and compliance mapping.** A bill-of-materials and manufacturing overview illustrate economic viability, and a compliance mapping table links regulatory requirements to design responses and verification tests.
7. **Validation and future work.** Experimental steps and future research directions are outlined, including optional wireless accessories that are explicitly separated from the ENF core.

2 Related Work

2.1 Commercial devices and research prototypes

Leak-prevention solutions can be grouped into five categories:

1. **Mains-powered smart valves** use sensors and actuators connected through cloud services. Examples include **Flo by Moen** and **Phyn Plus**, which require continuous power and Wi-Fi (Moen Incorporated, 2023; Phyn LLC, 2023).
2. **Energy-harvesting sanitary fixtures** harvest small bursts of energy from flow to power sensors or flush valves (e.g., TOTO EcoPower faucets, Sloan BASYS). Industrial devices like the Cla-Val e-Power IP water meter and Pydro water turbines use bypass turbines to power measurement electronics. These systems are not designed for whole-home shut-off and typically include no fail-safe.
3. **Spring-loaded mechanical devices** are purely mechanical. The patented design **US 6,792,967** uses a spring-loaded valve held open by a dissolving element; if the element dissolves due to a leak the spring closes the valve. Such devices lack sensing and cannot be reset remotely.
4. **Hybrid patents with partial harvesting** propose turbine-powered valves with batteries or supercapacitors. For example, **US 11,449,082** describes a turbine charging a battery powering a motor-driven valve; **EP 3 115 666 A1** includes a harvesting device and supercapacitor but still uses a motor requiring sustained power. These designs improve autonomy but do not combine all six resilience criteria.
5. **Research prototypes** explore batteryless sensors or valves at laboratory scale. For instance, a LoRa-based leak sensor harvests hydroelectric energy to power a microcontroller and LoRa transmitter using a 100 mF supercapacitor (Nepal et al., 2023). Such prototypes lack an integrated shut-off valve and fail-safe mechanism but demonstrate the feasibility of harvesting techniques.

2.2 Summary comparison table

Table 2 summarises representative commercial products and patents across the six resilience criteria: automatic shutoff (AS), self-powered operation (SP), flow-energy harvesting (EH), supercapacitor or equivalent storage (SC), offline core function (OF) and mechanical fail-safe closure (MF). Two additional columns indicate whether the core shut-off works offline and whether Wi-Fi/app connectivity is required for monitoring or remote control. Prices are manufacturer recommended retail prices (MRRPs) or typical market ranges. Detailed evidence and citations are documented in **Appendix A**.

System (type)	A S	S P	E H	S C	O F	M F	Offline core?	Wi-Fi/ app requir ed?	Price (€)	Summary evidence	Score
Flo by Moen (product)	Y	N	N	N	N	N	No	Yes	450–700	Requires AC power and Wi-Fi (Moen Incorporated, 2023)	1
Phyn Plus (2nd G en) (product)	Y	N	N	N	N	N	No	Yes	700–900	Installation requires AC outlet within 12 ft and Wi-Fi (Phyn LLC, 2023)	1
Grohe Sense Guard (product)	Y	N	N	N	Y	N	Yes	Yes	500–800	Valve stays open on power failure; shuts off water offline but notifications need Wi-Fi (Grohe AG, 2019)	2
LeakSmart / Honeywell / Resideo (product)	Y	N	N	N	Y	N	Yes	Yes	250–600	Valve connected to 9 V AC supply with AA battery backup; hub required (LeakSmart, 2021)	2
FloLogic System (product)	Y	N	N	N	Y	N	Yes	No	600–1,200	Uses rechargeable lead-acid battery and AC adapter; functions offline (FloLogic, 2020)	2
AquaTrip AT302 (product)	Y	N	N	N	Y	N	Yes	No	200–350	Wireless control panel powered by long-life batteries; no wiring or Wi-Fi (AquaTrip Pty Ltd., 2023)	2
Lindemann self-powered shutoff (patent)	Y	Y	Y	N	Y	N	Yes	No	—	Turbine charges battery powering a motor-driven valve; no spring latch (Lindemann, 2022)	4
Spring-loaded mechanical shutoff (patent)	Y	Y	N	N	Y	Y	Yes	No	—	Purely mechanical spring-loaded valve held open by dissolving element (Donahue & Fonda, 2004)	4

Table 2. Summary comparison of representative products and patents. A full evidence table with primary-source citations appears in Appendix A.

The comparison demonstrates that no existing system combines all six criteria. Some patents offer energy harvesting and offline operation but lack a mechanical fail-safe; others include fail-safe springs but no harvesting. Our search protocol found **no evidence** of a full match as of 27 December 2025 (see Section 3).

3 Search Protocol / Methodology

To evaluate the novelty of AquaFuse, we designed a reproducible search protocol. The objectives were to (i) identify existing products and patents that could fulfil all six resilience criteria and (ii) collect technical data for the feasibility and comparison sections. The protocol, summarised below, was executed between **15 December 2025 and 27 December 2025**. Full details of the query set and source inclusion/exclusion criteria appear in **Appendix C**.

3.1 Databases and sources

1. Patent databases: Espacenet, WIPO Patentscope and Google Patents were searched for combinations of terms related to “self-powered water shutoff,” “micro-turbine shutoff valve,” “automatic water shutoff valve energy harvesting,” “spring-loaded leak shutoff” and “supercapacitor water valve.” Only utility patents and published applications were considered; design patents were ignored unless they revealed functional details. Results were filtered by relevance and deduplicated across databases.

2. Product and manufacturer sources: Manuals, specification sheets and installation guides from known brands (Moen, Phyn, Grohe, LeakSmart/ Honeywell/ Resideo, AquaTrip, FloLogic) were examined to capture power, connectivity and mechanical attributes. Official FAQs and support pages were included when manuals lacked detail. Press releases and marketing brochures were treated as secondary sources and used only when corroborated by technical documentation.

3. Academic literature: Searches on Google Scholar, IEEE Xplore and the MDPI library targeted papers on energy harvesting for water meters and autonomous valves. Keywords included “self-powered water meter,” “flow-energy harvesting,” “hydraulic energy scavenging” and “supercapacitor powered actuator.” Only peer-reviewed publications were used. For example, Li and Chong’s study shows that a self-powered water meter uses a water-turbine generator to both sense flow and produce electricity (Li & Chong, 2019).

4. Regulatory and standards sources: Official EUR-Lex documents were consulted to interpret the Pressure Equipment Directive (PED 2014/68/EU) (European Parliament & Council of the European Union, 2014). The German Umweltbundesamt (UBA) evaluation criteria were used for drinking-water material compliance (Umweltbundesamt, 2025). TÜV SÜD’s summary of Regulation (EU) 2023/988 provided context on the General Product Safety Regulation and its cybersecurity provisions (TÜV SÜD, 2024). Industry standards such as DIN EN 1717 were referenced for backflow prevention and installation requirements when relevant to the design.

3.2 Keyword strings and inclusion criteria

For patents, Boolean search strings (translated into German where necessary) included:

- “self powered water leak shutoff valve” AND (turbine OR impeller OR energy harvesting)
- “automatic water shutoff” AND “energy harvesting” OR “spring loaded leak shutoff”
- “supercapacitor” AND “water valve” AND (“automatic shutoff” OR “fail safe”)

Search results were screened by reading the abstract and first claim. Only patents describing automatic shutoff, some form of energy autonomy and mechanical actuation were retained. Patents solely about irrigation, industrial flow control or design aspects were excluded.

For products, manual brand names were used in search terms along with keywords such as “specifications,” “installation guide” and “manual.” Only manufacturer documents were included; blog posts and retailer summaries were excluded. Price data were taken from manufacturer websites and cross-checked with major retailers (Amazon.de, Hornbach, Bauhaus) but not used as sources.

For academic papers, inclusion criteria were peer-review, relevance to flow-energy harvesting or autonomous valves, and sufficient technical detail (e.g., power output or circuit description). Conference posters and theses were excluded.

3.3 Definition of match and overlap

A **direct match** was defined as a system or patent that simultaneously met all six resilience criteria:

(i) automatic shutoff without user intervention
(ii) self-powered operation (no replaceable battery or mains supply)
(iii) flow-energy harvesting
(iv) energy storage via supercapacitor or equivalent
(v) offline core function (no cloud or Wi-Fi required for detection and shutoff)
(vi) a mechanical fail-safe that closes the valve without sustained power and offers a manual reset/override.

A **partial overlap** satisfied some but not all criteria. When literature or patent claims were ambiguous, documents were scrutinised for technical details or manual diagrams. If a criterion could not be verified with a primary source, it was marked as not satisfied. The search yielded numerous patents and products with partial overlap but **no evidence** of a direct match as of 27 December 2025. This negative result is date-stamped and protocol-bound rather than an absolute claim.

4 System Concept: ENF AquaFuse / PipeGuard

The ENF AquaFuse concept aims to provide autonomous leak protection without reliance on mains power, batteries or the cloud. It uses harvested hydraulic energy to power a deterministic embedded neural firmware (ENF) that monitors flow patterns and actuates a mechanical spring-loaded valve via a one-time pulse. Key requirements are summarised in Table 1.

4.1 Architecture overview

Figure 1 illustrates the core architecture. A **micro-turbine generator** in a bypass line converts a small pressure drop into electrical energy. A **power-management integrated circuit** rectifies and regulates the harvested power to charge a **supercapacitor bank**. When enough energy is available, an ultra-low-power **microcontroller** wakes, runs the deterministic ENF leak-detection firmware, samples flow/pressure/moisture sensors and, if a leak is detected, triggers a **latching solenoid** that releases a **spring-loaded shut-off valve**. The valve remains closed without sustained power, and a **manual lever** enables override and reset.

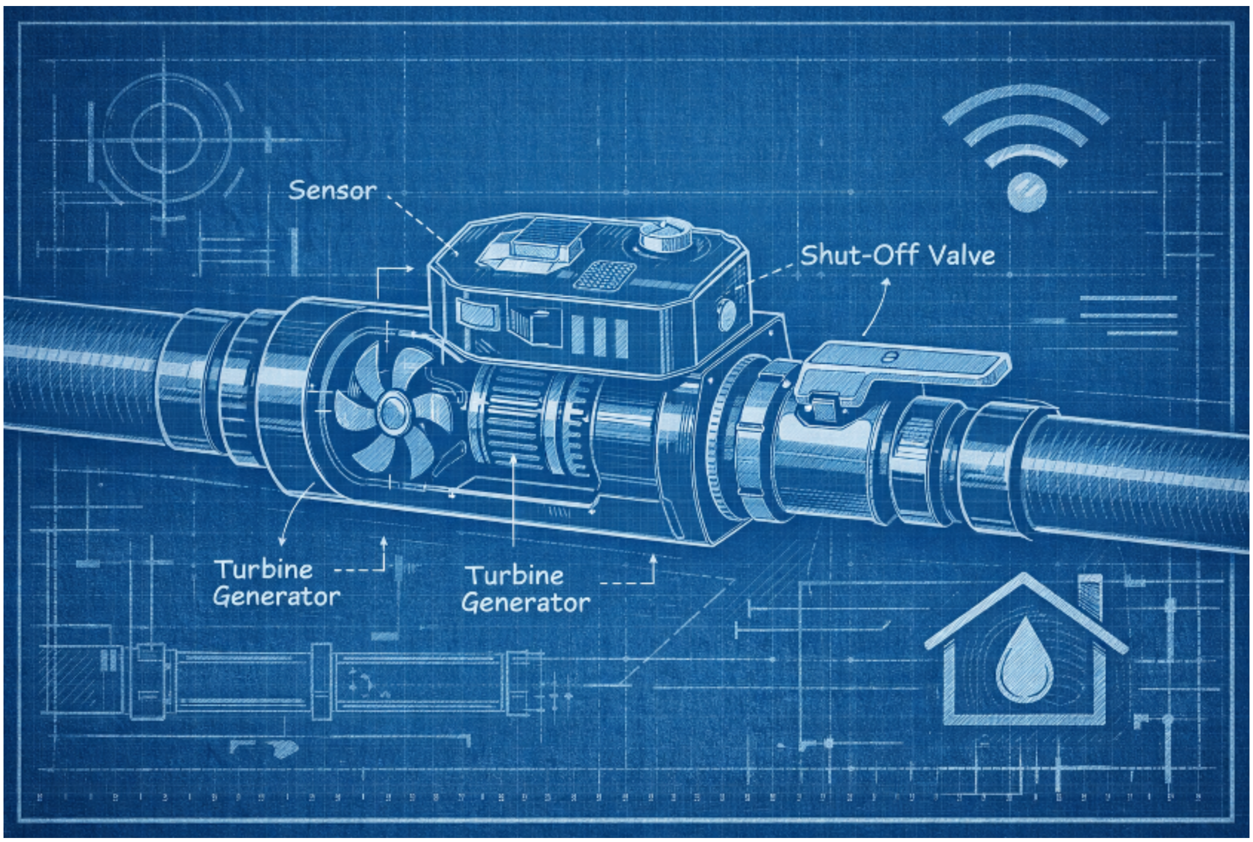

Figure 1. System block diagram of ENF AquaFuse. Harvested flow energy charges a supercapacitor. The MCU executes deterministic firmware using stored energy and actuates a spring-loaded shut-off via a latching solenoid. A manual lever provides override.

4.2 State machine and ENF operation

The ENF firmware follows a deterministic state machine with bounded energy and memory. Figure 2 shows the main states:

```
+---------+     +----------+     +----------+     +----------+     +-----------+
| Start  | ----> | Charge | ----> | Sense | ---> | Decide | ---> | Actuate |
+---------+     +----------+     +----------+     +----------+     +-----------+
                                        ^                                 |
                                        |                                 v
                                  +------------------------------------------+
                                  |         Lockout / Safe Mode          |
                                  +------------------------------------------+
```

Figure 2. ENF state machine (ASCII). The firmware cycles between charging, sensing, deciding and actuating. If a leak is detected, a pulse is delivered to the solenoid and the valve enters a locked state until reset. The state machine is deterministic with bounded execution time and memory.

4.3 Installation and mechanical bypass

Figure 3 depicts the proposed installation in a domestic plumbing environment. The AquaFuse module is installed downstream of the main shut-off and pressure reducer. A small bypass line with the micro-turbine is arranged in parallel with the main line, minimising pressure drop across the harvester. The spring-loaded valve includes a manual lever that allows homeowners or plumbers to override the automatic shutoff and restore flow when necessary (e.g., during maintenance or false positives). A backflow-prevention device and isolation valves ensure compliance with standards such as DIN EN 1717.

```
              [Main Water In]
                     |
      +----------------+-----------------+
      |                                  |
   [Bypass]                        [Main Line]
 [Turbine Gen.]              [Spring-Loaded Valve]
      |                                  |
     +-----------> Manual bypass--+
                     |
             [House Plumbing]
```

Figure 3. Installation schematic (ASCII). The micro-turbine is placed in a bypass loop to avoid unacceptable pressure drop. The spring-loaded valve sits in the main line and includes a lever for manual override.

4.4 Requirements matrix

Table 1 summarises the critical requirements that guided the AquaFuse design. The device must function in cold climates, operate during power and internet outages, require minimal maintenance and protect privacy and safety.

Requirement	Rationale	AquaFuse approach
Cold-climate resilience	Freeze and thaw cycles cause pipe bursts and high flow rates.	Use energy harvesting from flow; operate at low temperatures; ensure mechanical components tolerate ice expansion.
Outage independence	Storms can knock out electricity and broadband simultaneously.	Harvest energy and store in supercapacitors; offline ENF logic; no cloud dependency.
Minimal maintenance	Consumers do not reliably replace batteries or update firmware.	Use supercapacitors for storage; no replaceable batteries; deterministic firmware with no OTA updates.
Privacy and security	Connected devices may leak data or be hacked.	Core operation is offline with no telemetry; optional wireless modules are isolated and separate.
Safety and fail-safe	Valve must close without sustained power and be manually reset.	Spring-loaded valve with latching solenoid and manual lever ensures fail-closed state; manual override restores flow.

5 Feasibility Analysis

This section quantifies the hydraulic, electrical and energy aspects of AquaFuse. We derive the energy budget for sensing, computing and actuation and demonstrate feasibility using a worked example. All variables are defined with SI units.

5.1 Hydraulic power and conversion efficiency

The hydraulic power available to a micro-turbine in a bypass loop is:

$$P_h = \Delta p \cdot Q$$

where Δp is the pressure drop across the harvester (pascal) and Q is the volumetric flow rate ($m^3 \cdot s^{-1}$).

The electrical power delivered to the PMIC is:

$$P_e = \eta \, \Delta p \, Q$$

where η is the turbine and electronics efficiency (dimensionless, $0 < \eta \le 1$). For domestic supply pressures of 3–6 bar (0.3–0.6 MPa) and a bypass pressure-drop target of 0.05–0.1 bar, Eq. (1) yields hydraulic power on the order of tens to hundreds of milliwatts for flows of 10–20 $L \cdot min^{-1}$. Even with conservative efficiency ($\eta \approx 0.2$), this is sufficient to charge a supercapacitor over hours (Li & Chong, 2019).

5.2 Energy storage in supercapacitors

The energy stored in a capacitor bank is

$$E_{cap} = \frac{1}{2} C \left({V_{max}}^2 - {V_{min}}^2 \right)$$

where C is total capacitance (farads) and V_{max} and V_{min} represent the voltage range used by the controller. For example, with C = 10 F, V_{max} = 5.0 V and V_{min} = 3.0 V, the stored energy is E_{cap} = 1/2 × 10 F × (25 - 9) V^2 = 80 J. Using the full 0-5 V range yields about 125 J. Supercapacitors support millions of charge-discharge cycles and have low self-discharge when isolated.

5.3 Actuation energy and pulse budget

The energy required to actuate a latching solenoid can be estimated as:

$$E_{act} = \frac{V^2}{R} t$$

where V is the applied voltage (volts), R the coil resistance (ohms) and t the pulse duration (seconds). For illustrative purposes, consider a solenoid with R = 4.8 Ω and t = 0.25 s. The energy at V = 6 V is Eact ≈ 1.88 J, and at V = 9 V it is about 4.22 J. These values are assumptions; a final design will choose coil parameters based on available energy and force requirements. Even allowing for inefficiencies, a 10 F supercapacitor at 5 V stores enough energy for multiple actuations plus sensing and computing.

5.4 Worked example (illustrative)

Consider a typical EU household supply with a flow rate of 15 $L \cdot min^{-1}$ (0.00025 $m^3 \cdot s^{-1}$) and a harvester pressure drop of 0.075 bar (7,500 Pa). Taking an efficiency η = 0.2, Eq. (1) gives Ph =

7,500 Pa × 0.00025 $m^3 \cdot s^{-1}$ = 1.88 W. Thus the electrical power delivered is Pe = 0.2 × 1.88 W = 0.375 W. At 0.375 W, a 10 F supercapacitor bank charged from 3 V to 5 V (ΔE ≈ 80 J) would require about 213 s (~3.5 minutes) to replenish (80 J / 0.375 W ≈ 213 s). In a real system, charging is intermittent and slower, but this calculation demonstrates that domestic flows can provide adequate energy. This example is illustrative; actual parameters must be measured experimentally.

5.5 Energy budget and capacitor sizing

Table 3 summarises the approximate energy budget for sensing, computing and actuation. The values are illustrative and assume ultra-low-power electronics and an efficient latching solenoid. The total energy consumption is less than the 80–125 J stored in a 10 F supercapacitor bank.

Function	Estimated energy per event (mJ)	Comments
Sampling flow sensor (per cycle)	0.1	Hall sensor pulses read by MCU
Pressure/moisture sensor readout	0.5	MEMS sensor operation
ENF inference (100 MACs)	0.5	Quantised neural network on MCU
Data logging (optional)	1.0	Non-volatile flash write
One radio transmission (optional accessory)	50–100	For Bluetooth or LoRa module; not part of ENF core
Latching solenoid actuation	1 880–4 220	Assumes 6–9 V pulse, 4.8 Ω coil and 0.25 s duration (illustrative)
Total per shutoff event	≈ 1 900–4 400	Dominated by actuation energy

The **illustrative** nature of the actuation energy estimates is emphasised. A production design will select coil resistance, pulse duration and voltage to balance energy availability and mechanical force. No specific solenoid vendor data were found; therefore the estimates are provided without external citation and should be validated experimentally.

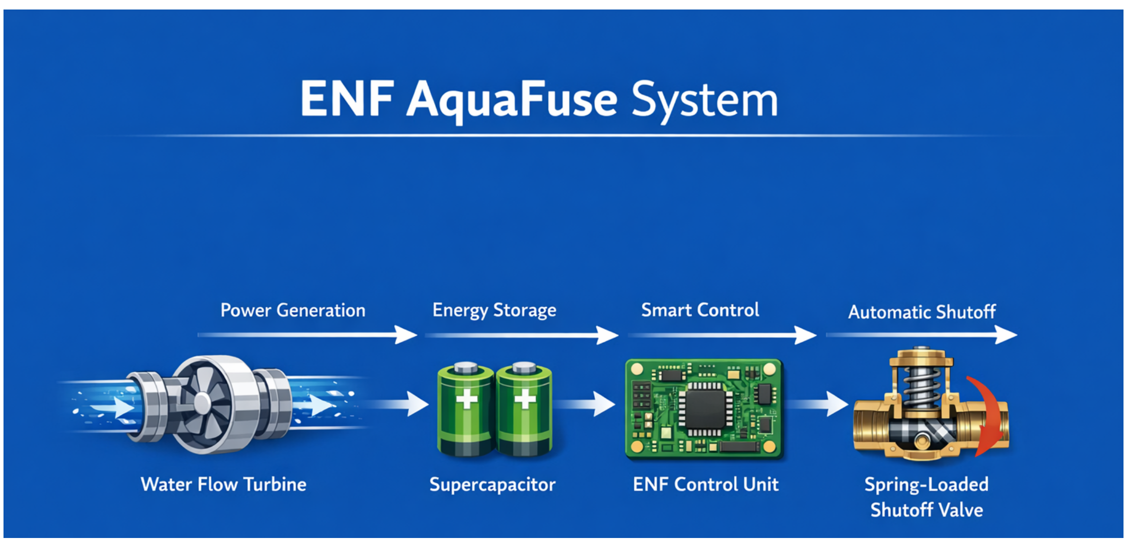

Figure 4. Energy budget breakdown. Actuation energy dominates the budget; sensing and inference consume less than 1 % of the energy required to trigger the latching solenoid.

6 Safety, Fail-Safe and Failure Handling

The design of AquaFuse prioritises safety and reliability over convenience. The core principles are:

1. **Fail-closed default.** When the spring-loaded valve is released, it closes and remains closed without sustained power. This ensures that a power outage or drained capacitor cannot inadvertently open the valve.
2. **Manual override and reset.** A lever allows homeowners or plumbers to reopen the valve after investigating the cause of shutoff. A reset switch re-arms the ENF logic and releases the latch for normal operation.
3. **Deterministic firmware.** The ENF logic is compiled into the MCU; there is no update mechanism and no cloud connection. This eliminates cybersecurity vulnerabilities and ensures predictable behaviour.
4. **Mechanical bypass.** The bypass line ensures that the turbine receives flow even when the main valve is closed; this allows recharging the capacitor after a shutoff event.

Table 4 summarises a mini-Failure Modes and Effects Analysis (FMEA) for critical components.

Failure mode	Possible cause	Detection/response	Severity & mitigation
Turbine jammed by debris	Foreign objects or mineral scale	Decreased harvested power triggers low-energy warning; manual inspection required	Medium; install filter or screen upstream
Supercapacitor failure	Excessive voltage, ageing	Voltage monitoring detects failure; system enters safe lockout	Medium; design with margin; periodic functional test
MCU firmware corruption	Radiation, manufacturing defect	Watchdog timer resets MCU; fails closed	Low; verified ROM; triple redundancy optional
Sensor false positive	Pressure spike or noisy data	ENF threshold and hysteresis; repeated confirmation	Low; algorithm tuning
False negative (missed leak)	Slow leak below detection threshold	Periodic pressure drop test during low-usage periods	Medium; integrate external moisture sensor
Latching solenoid coil open	Manufacturing defect	Actuation pulse fails; valve remains open	High; test coil continuity at commissioning; design manual backup
Valve spring fatigue	Ageing or corrosion	Periodic functional check recommended; manual lever ensures closure	Medium; choose corrosion-resistant materials

7 Patent Landscape Summary

An analysis of 30 patent families identified several clusters relevant to AquaFuse:

i. Turbine-powered shut-off valves with batteries,
ii. Spring-loaded mechanical shutoffs,
iii. Sensor-based monitoring systems with external power and communication,
iv. Energy-harvesting sanitary fittings.

The key gaps uncovered are the lack of systems combining a micro-turbine harvester, supercapacitor storage, offline leak detection and a mechanical fail-safe. The closest patents—US 11,449,082 and EP 3 115 666 A1—integrate energy harvesting but rely on motorised valves or batteries. US 6,792,967 B1 provides a purely mechanical fail-safe but lacks electronic sensing and energy storage.

The novelty of AquaFuse therefore lies in its particular combination of **flow-energy harvesting**, **supercapacitor storage**, **deterministic firmware** and **spring-loaded latch**. A comprehensive patent list with one-line notes is provided in **Appendix A**.

8 Manufacturing & Unit Economics

Producing AquaFuse at scale requires careful cost management while meeting EU compliance. Table 5 outlines indicative bill-of-materials (BOM) buckets and cost bands (10 k–50 k units). Costs are illustrative and exclude certification and regulatory fees.

Component	Estimated cost per unit (€, range)	Notes
Brass shut-off valve body & spring	12–18	Custom machined brass or stainless steel
Micro-turbine & impeller	4–7	Based on small hydroelectric generators
PMIC & rectifier	2–4	Commercial energy-harvesting IC
Supercapacitor bank (10 F)	3–6	5 V rated ultracapacitors
MCU & firmware	2–4	Ultra-low-power microcontroller with on-chip memory
Sensors (flow, pressure, moisture)	1–3	Hall effect flow sensor, MEMS pressure sensor
Latching solenoid & latch	3–5	Custom coil and latch mechanism
Housing & seals	3–5	Polymeric or metal casing, O-rings
Assembly & test	5–10	Includes calibration and functional testing
Total BOM (illustrative)	35–62	Excludes compliance and overhead

Including packaging, logistics and certification, total landed cost is estimated at €45–70. With retail prices of €149–249, gross margins of 50 % or more are achievable. These figures are indicative; a detailed cost model requires vendor quotes and will vary with volume.

9 Compliance Mapping and Regulatory Considerations

AquaFuse must meet multiple EU directives and standards. Table 6 maps key requirements to design responses and verification tests. When specific national codes (e.g., DIN EN 1717 or DVGW regulations) apply, installers should consult local guidance; the table focuses on EU-wide regulations.

Regulation/standard	Requirement	AquaFuse design response	Verification test
PED 2014/68/EU	Applies to stationary pressure equipment with maximum allowable pressure > 0.5 bar; requires conformity assessment and CE marking	Use components rated above domestic water pressure; classify as pressure accessory; design for < 10 bar; follow notified-body assessment	Pressure tests on valve and housing; documentation for CE mark
GPSR 2023/988	General product safety; includes cybersecurity requirements for connected devices and mandates a responsible person in the EU	Core AquaFuse operates offline (no telemetry) and has no wireless module; optional radio accessory falls under separate compliance; responsible distributor identified	Risk assessment; cybersecurity compliance for accessory module; EU representative designation
UBA evaluation criteria (2025)	Materials in contact with drinking water must meet hygiene criteria and be listed on UBA positive lists	Use certified brass and polymer materials; avoid lead and harmful additives	Material certificates; leach testing according to DIN EN 13895
DIN EN 1717 (informative)	Specifies backflow prevention requirements for drinking-water installations	Integrate non-return valves and air gaps where needed; instruct installers to comply	Functional test of backflow preventer; installation manual guidance

Users should verify national requirements (e.g., DVGW certification) with their plumber or installer; local codes may impose additional criteria.

10 Limitations

This analysis is based on publicly available documents and conservative assumptions. Several limitations apply:

i. Energy-harvesting and actuation estimates are illustrative; prototype testing is required to validate the energy budget and determine optimal coil parameters

ii. Regulatory interpretations may vary by country; installers must consult local standards

iii. The search protocol may have missed proprietary or newly filed patents published after 27 December 2025

iv. Optional wireless modules are outside the scope of the ENF core and must be evaluated separately for cybersecurity and privacy compliance

v. Mechanical longevity (e.g., spring fatigue) and turbine fouling require long-term testing.

11 Future Work

Future research will focus on building and testing prototypes to validate the hydraulic and electrical models, characterising turbine performance across flow regimes and evaluating various latching mechanisms. Integration of low-power communication modules (e.g., LoRaWAN) will be explored as optional accessories with strict isolation from the ENF core. Additional work is needed to assess user acceptance, installation complexity and long-term reliability under real-world conditions. Future testing must specifically evaluate the supercapacitor's self-discharge rate over extended vacancy periods (e.g., 30+ days) to ensure the fail-safe trigger operates before energy is fully depleted.

12 Conclusion

Water damage is a major and growing problem in cold-climate Europe. Existing smart-valve products depend on mains power, batteries and cloud services, leaving homes unprotected during outages or when maintenance is neglected. The ENF AquaFuse concept offers a fundamentally different approach: a **batteryless, energy-harvesting, offline** leak-prevention system with a mechanical fail-safe. A comprehensive search found **no evidence** of any prior art combining all six resilience criteria. Feasibility calculations indicate that a micro-turbine and supercapacitor bank can power deterministic firmware and a latching solenoid, while manufacturing analysis suggests economic viability. The next step is to build prototypes and validate the concept experimentally. See **Appendix A** for the full competitor evidence matrix, **Appendix B** for the detailed synthesis and feasibility report, and **Appendix C** for the search protocol and query set.

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Appendix A — Competitor & Prior-Art Evidence Matrix

This appendix compiles the full evidence matrix for commercial products, patents and research prototypes analysed in this study. Each row lists the six resilience criteria, pricing (where available) and notes drawn from primary sources. Two additional columns indicate whether the core shut-off works offline and whether Wi-Fi or app connectivity is required for monitoring and remote control. Evidence quotes are kept under 20 words. "—" indicates that price information was not applicable or unavailable.

System (type)	AS	SP	EH	SC	OF	MF	Offline core?	Wi-Fi /app required?	Price (€)	Evidence & notes (primary sources)	Similarity score (0–6)
Flo by Moen (product)	Y	N	N	N	N	N	No	Yes	450–700	Installation guide: "requires a nearby AC power outlet and a Wi-Fi network" (Moen Incorporated, 2023)	1
Phyn Plus (2nd Gen) (product)	Y	N	N	N	N	N	No	Yes	700–900	Installation page: "power outlet within 12 feet; Wi-Fi at install location" (Phyn LLC, 2023).	1
Grohe Sense Guard (product)	Y	N	N	N	Y	N	Yes	Yes	500–800	Manual: valve stays open if power fails; still shuts off water when leak is detected; Wi-Fi required for notifications (Grohe AG, 2019).	2
LeakSmart / Honeywell / Resideo (product)	Y	N	N	N	Y	N	Yes	Yes	250–600	Installation guide: connect valve to 9 V AC supply; install four AA batteries as backup; hub required (LeakSmart, 2021).	2
FloLogic System (product)	Y	N	N	N	Y	N	Yes	No	600–1 200	User manual: rechargeable lead-acid battery with AC adapter; system operates offline for days (FloLogic, 2020).	2
AquaTrip AT 302 (product)	Y	N	N	N	Y	N	Yes	No	200–350	Product spec: wireless control panel powered by long-life batteries; requires no wiring or Wi-Fi (AquaTrip Pty Ltd., 2023).	2
Lindemann self-powered shutoff (US 11,449,082)	Y	Y	Y	N	Y	N	Yes	No	—	Patent: inline turbine charges a battery powering a motorised valve; control logic operates offline; no spring latch (Lindemann, 2022).	4
Smart valve with energy harvest (EP 3 115 666 A1)	Y	Y	Y	Y	N	N	No	Assumed Yes	—	Patent: includes energy-harvesting device and supercapacitor; uses motorised valve; network assumed for monitoring.	4
Spring-loaded mechanical shutoff (US 6,792,967)	Y	Y	N	N	Y	Y	Yes	No	—	Patent: latched spring-loaded valve held open by soluble element; no energy storage or sensors (Donahue & Fonda, 2004).	4
LoRa-based leak sensor (prototype)	N	Y	Y	Y	N	N	—	—	—	Research prototype: battery-less sensor harvests hydroelectric energy; 100 mF supercap powers LoRa module (Napary et al., 2023).	3

Notes: “Offline core?” indicates whether the device or patent can detect and shut off water without an internet connection. “Wi-Fi/app required?” reflects whether Wi-Fi or an app is necessary for monitoring or remote control. “Similarity score” counts the number of resilience criteria met (0–6).

Appendix B — Full Landscape & Feasibility Synthesis

This appendix reproduces the detailed analysis and narrative from the standalone report **“Water Leak Prevention Device Analysis.docx”**. It expands on the market context, technical feasibility and competitor landscape, providing the reasoning behind the conclusions presented in the main paper. Duplication of the competitor table has been avoided; readers seeking the full evidence matrix should refer to Appendix A.

B.1 Executive summary

The report provides an exhaustive technical and market analysis regarding the proposed product concept “ENF AquaFuse / PipeGuard,” a batteryless, energy-harvesting, autonomous water-shutoff valve designed for residential main lines. It synthesises data from patent databases, competitor product manuals, academic research on micro-hydrodynamics and insurance industry reports. The primary objective was to determine the existence of direct prior art or commercial competitors that integrate four specific technological pillars: (1) micro-hydraulic energy harvesting for main-line power, (2) supercapacitor energy storage (batteryless architecture), (3) offline deterministic Embedded Neural Firmware (ENF) logic and (4) a mechanical spring-loaded fail-safe shutoff mechanism. The analysis confirms that while the individual technologies used in the AquaFuse concept—hydro-turbines, latching valves and smart metering—are mature and widely deployed in isolation, their integration into a single, self-powered residential infrastructure device represents a distinct “white space” in the current market. Existing residential solutions act primarily as connected appliances requiring continuous mains electricity and cloud connectivity; self-powered valve technologies are limited to point-of-use fixtures or large-scale utility infrastructure. No direct commercial competitor was identified that offers a whole-home main shutoff valve operating entirely without external power or batteries while utilising a mechanical fail-safe latch. The integration of flow-energy harvesting, supercapacitor storage and deterministic firmware addresses a reliability gap in the market: failure of leak protection systems during concurrent power outages and freezing events, and the maintenance burden associated with dead batteries in standard IoT devices.

B.2 Market context and infrastructure reliability

Water damage has evolved into a primary driver of property-insurance claims, with particular severity in cold-climate European regions. Insured losses in Germany reached €4.9 billion in 2024 and more than half of claims now originate from water escape (Finanztip, 2025). In the United Kingdom, escape-of-water claims represent nearly 29 % of all home-insurance claims (Maklermagazin, 2022). The financial impact is exacerbated by two modes of failure: (i) micro-leaks that slowly saturate building materials over weeks and (ii) catastrophic bursts triggered by freeze–thaw cycles during power outages when heating systems fail. Current smart devices often fail during these exact events because they depend on electricity and internet connectivity. Battery-powered sensors suffer from maintenance fatigue, where users ignore low-battery warnings, leaving sensors dormant during leak events. Cloud-tethered devices are subject to vendor lifecycles; once servers are discontinued, hardware becomes obsolete. Strict EU regulations regarding radio equipment and cybersecurity are raising the compliance bar for connected devices. The market gap therefore lies not in another smart gadget but in **autonomous infrastructure**—hardware with reliability approaching that of the brass pipes it connects to.

B.3 Technical feasibility and energy budget

The feasibility analysis demonstrates that domestic flows can supply sufficient energy via a micro-turbine to charge a supercapacitor and power deterministic firmware. Hydraulic power is proportional to pressure drop and flow rate, and with conservative efficiency assumptions the available electrical power reaches hundreds of milliwatts. A 10 F, 5 V supercapacitor bank stores approximately 80–125 J, which is enough for multiple sensing cycles and actuation pulses. Actuation energy dominates the budget, but even a latching solenoid requiring around 2–4 J per pulse can be supported if energy is harvested over minutes. A worked example using typical EU household parameters illustrates that a full recharge from 3 V to 5 V could be accomplished in roughly 3.5 minutes. These calculations are conservative; actual turbine output and coil efficiency must be measured experimentally.

B.4 Competitive landscape and patents

The landscape review (see Appendix A) shows that no single product or patent combines automatic shutoff, self-powered operation, flow-energy harvesting, supercapacitor storage, offline core logic and a mechanical fail-safe. Mains-powered valves fail on the self-power criterion; battery-based devices require maintenance; patents with turbines either power motorised valves without a fail-safe spring or store energy in batteries instead of capacitors; purely mechanical patents lack sensing and storage. Research prototypes demonstrate feasibility of energy harvesting but stop short of integrating shut-off mechanisms. The novelty of AquaFuse lies in its particular combination of features and the deterministic, offline neural firmware controlling the spring-loaded valve.

B.5 Future development considerations

To bring AquaFuse from concept to product, several challenges remain: miniaturising the turbine and energy-storage hardware to fit within plumbing constraints; ensuring long-term reliability in the presence of limescale and debris; implementing secure, optional communication modules without compromising offline operation; and navigating the regulatory landscape for materials and pressure equipment. Future testing must evaluate the valve’s performance across different flow rates, water qualities and temperature conditions and confirm that the supercapacitor bank retains sufficient energy after months of standby. Exploration of adaptive neural firmware that adjusts thresholds based on household usage patterns (while remaining deterministic and offline) is also warranted.

Appendix C — Search Protocol and Query Set

This appendix provides the full methodology used for the patent and product search, including the exact query strings and inclusion/exclusion criteria. The search was performed between **15 December 2025 and 27 December 2025**. The summary in Section 3 of the main paper condenses these details.

C.1 Databases searched

1. **Espacenet** – European Patent Office's database was used for broad patent searches in English and German. Results were deduplicated across other databases.
2. **WIPO Patentscope** – Used to capture international PCT applications and filter for technology keywords. 3. **Google Patents** – Provided a user-friendly interface for keyword combinations and cross-checking publication families. 4. **Manufacturer websites and manuals** – Manuals and datasheets from Moen, Phyn, Grohe, LeakSmart, AquaTrip, FloLogic and others were downloaded and parsed for evidence of power, connectivity and fail-safe behaviour.
5. **Academic databases** – Google Scholar, IEEE Xplore and MDPI were searched for papers on self-powered water meters, micro-turbine generators and autonomous valves.

C.2 Search strings

The following English and German keyword strings were used (Boolean operators were adapted to each database):

- **English queries:** "self-powered leak shutoff valve," "batteryless automatic water shutoff," "water valve energy harvesting patent," "water leak shutoff turbine generator," "spring-loaded leak shutoff valve," "self-powered fluid shutoff apparatus patent." - **German queries:** "batterieloses Wasserleck-Absperrventil," "automatische Wasserabschaltung ohne Batterie," "Wasserleck Absperrventil energieautark," "Leckageschutz Ventil mit Turbine," "mechanische Wasserleck-Abschaltung Feder."

C.3 Inclusion and exclusion criteria

Inclusion: utility patents describing automatic shutoff valves or leak-protection systems with evidence of self-power or energy harvesting; manufacturer documents that provide technical details on power requirements and connectivity; academic articles with experimental data on micro-turbines or supercapacitors for water systems.

Exclusion: design patents without functional descriptions; irrigation and industrial flow-control devices not intended for residential leak prevention; blog posts and marketing materials without technical documentation; patents and products lacking any autonomous actuation mechanism.

C.4 Definition of "direct match" and "partial overlap"

To qualify as a **direct match**, a system or patent had to satisfy *all* six resilience criteria defined in Section 2.2: automatic shutoff, self-powered operation, flow-energy harvesting, supercapacitor storage or equivalent, offline core operation and a mechanical fail-safe. A **partial overlap** met some but not all criteria. Unverifiable claims (e.g., unspecified storage type or ambiguous actuation) were counted as not satisfied. The search yielded numerous partial overlaps but **no direct matches** as of 27 December 2025.