The Evolution of European Solar-to-X Research: From Fundamental Material Science to the SPECTRUM Polygeneration Framework

Authors:
Prof. Marco Pellegrini, PhD
Dott. Rakshya Shrestha

Affiliation:
Interdepartmental Centre for Industrial Research in Renewable Resources, Environment, Sea and Energy (CIRI-FRAME), University of Bologna

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Abstract

The European Union's commitment to achieving climate neutrality by 2050 under the Green Deal and REPowerEU mandates rapid industrial decarbonization. However, the industrial sector remains heavily constrained by its reliance on fossil fuels primarily for process heat, high land-use competition, and growing environmental liabilities such as energy-intensive wastewater management. Traditional, single-product solar deployments (e.g., standalone photovoltaic or hydrogen facilities) fail to address this multi-vector energy-water nexus and suffer from poor economic viability.

This paper presents a systematic review of European Union-funded Solar-to-X (S2X) research across the FP7, Horizon 2020, and Horizon Europe framework programs. Employing a thematic evolutionary framework, the study evaluates project trajectories from early-stage material science breakthroughs (NanoPEC, ArtipHyction, PECDEMO) to multi-megawatt industrial scale-ups (HYDROSOL series, PECSYS) and the emerging polygeneration paradigm (PH2OTOGEN, GH2, SOL2HY2, DESIRED, Sun-To-X, SOLEAS).

By synthesising performance metrics, thermal dynamics, and co-product economics across these initiatives, this paper maps how historical lessons converge into the novel SPECTRUM framework. SPECTRUM introduces a decentralised concentrating collector that utilises physical spectral splitting to thermally decouple photovoltaic cells from absorbers, matching specific wavebands to high-efficiency processes: ultraviolet for simultaneous photocatalytic H2 evolution and industrial wastewater remediation, visible light for clean electricity, and infrared for high-temperature heat generation. Ultimately, this review establishes full-spectrum harvesting and circular polygeneration as the definitive blueprint for scalable, high-power-density industrial infrastructure.

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1. Introduction

In line with the European Green Deal and the REPowerEU plan, the European Union (EU) has set ambitious targets to achieve climate neutrality by 2050, placing immense pressure on member states to accelerate the deployment of clean energy technologies. However, the decarbonization of the industrial sector remains one of the most significant hurdles to this transition. At the EU level, the industrial sector is responsible for 26% of final energy consumption, 24% of greenhouse gas emissions, and 54% of wastewater produced. Crucially, the energy supply to this sector is heavily dominated by fossil fuels and relies on a massive demand for industrial heat, which accounts for 75% of industrial energy consumption across all temperature applications, while electricity accounts for the remaining 25%. Simultaneously, water scarcity and wastewater management represent growing global threats. Current wastewater treatment technologies are highly energy-intensive, and only 2.5% of treated wastewater is reused [1].

Attempting to meet these industrial energy demands with traditional, single-product renewable energy layouts (such as standard photovoltaic farms) requires vast amounts of land, intensifying global land-use competition and biodiversity loss. However, physical space is not the only limitation; a multi-product architecture is also an absolute necessity from an economic perspective. Single-product energy generation systems fundamentally underutilise the full potential of the invested infrastructure and struggle to achieve economic viability under real market conditions [1]. By transitioning to a polygeneration model that co-produces multiple energy vectors and value-added chemicals, facilities can maximise resource efficiency and unlock secondary revenue streams, which are essential for driving down production costs and ensuring market readiness [2], [3]. Therefore, the future of industrial sustainability demands a shift toward high-power-density, decentralised polygeneration systems deployed directly on artificialized industrial sites.

This paper synthesises the evolution of key EU-funded Solar-to-X projects, tracking the journey from fundamental lab-scale material breakthroughs to massive industrial integrations, to extract critical insights for the emerging SPECTRUM framework. These historical insights reveal that the future of industrial sustainability relies entirely on full-spectrum harvesting and polygeneration. Building directly upon these proven foundations, SPECTRUM represents the ultimate integration of solar technology. The project aims to develop groundbreaking concentrating collectors that fully harness the solar spectrum to co-generate three distinct renewable energy vectors: solar heat, solar electricity, and green hydrogen while simultaneously treating industrial wastewater. By employing advanced spectral splitting solutions, SPECTRUM thermally decouples the PV cells from the thermal absorber. It perfectly matches energy grades by using Ultraviolet (UV) and near UV visible (VIS) for dual-functional photocatalytic hydrogen production and pollutant degradation, VIS-near infrared (IR) for photovoltaic electricity, and IR for high-temperature heat generation, as shown in Figure 1. This approach converts waste into valuable solar fuel, providing a holistic and economically viable solution to the industrial energy-water nexus [4].

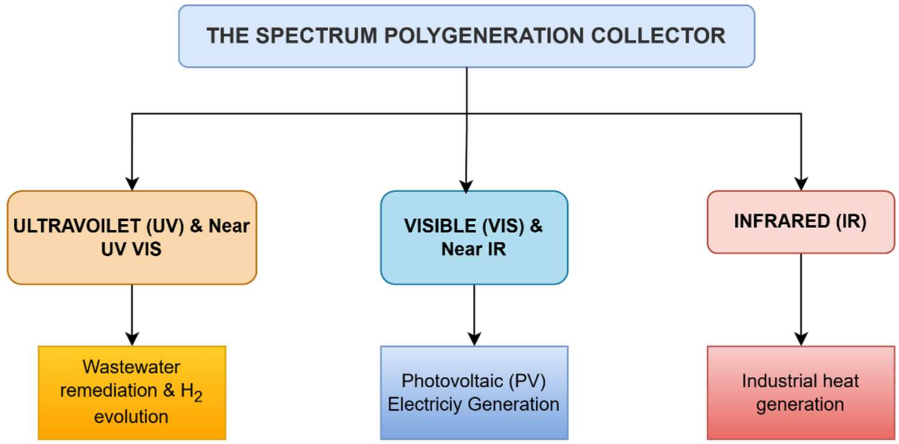

Figure 1 Spectral waveband allocation and multi-vector polygeneration in the SPECTRUM architecture.

2. Methodology

This paper conducts a targeted review of European Union-funded Solar-to-X (S2X) research initiatives spanning the FP7, Horizon 2020, and Horizon Europe frameworks. To systematically evaluate the historical and technological landscape of European Solar-to-X (S2X) technologies, the study filters projects based on their technical data, project objectives, and physical outcomes across diverse pathways, including photoelectrochemical (PEC) water splitting and solar thermochemical cycles.

Rather than a generic chronological summary, the methodology employs a thematic clustering approach. The identified projects are categorised into distinct evolutionary stages based on their technological pathways and operational scale: initial material science breakthroughs at the lab scale, subsequent leaps into large-scale industrial systems, and the recent shift toward the polygeneration paradigm. Within these clusters, the synthesis critically evaluates physical performance metrics, including solar-to-hydrogen (STH) conversion efficiencies, reactor scaling dynamics, and long-term operational stability, to assess technological maturity.

Specifically, the analysis deliberately filters the historical project data to isolate three critical advancements: multi-spectrum solar utilisation, dynamic control platforms, and the synergistic polygeneration of multiple energy vectors (such as electricity or heat) and value-added chemicals alongside green hydrogen. By tracing these specific technological threads across decades of European research, this methodology systematically isolates the foundational building blocks required for next-generation architectures. This approach logically maps how the fragmented lessons of past projects converge to justify and inform the highly integrated design of the emerging SPECTRUM framework.

3. Project Synthesis

To systematically evaluate the European Solar-to-X (S2X) landscape, the identified projects have been grouped into four distinct technological clusters based on their chemical pathways and operational scale.

3.1 First-Generation Breakthroughs: Cracking the Science of Solar Harvesting

Early EU framework initiatives (FP7) were heavily focused on overcoming fundamental bottlenecks in materials science to demonstrate that solar-driven chemical production was viable.

• Nanostructured Photoelectrodes for Energy Conversion (NanoPEC | 2009–2011 | €3,589,188.00)

Aiming to overcome basic material limitations in photoelectrochemical water splitting, this project realised that no single material could meet all efficiency and stability requirements. Instead, NanoPEC designed composite nanostructures where each component performed specialised functions, originally targeting a 1 cm² device with a sustained 10% efficiency and a maximum performance decay of 10% over 5,000 hours. Delivering on this philosophy, the project achieved a photocurrent record of 7.6 mA cm^{-2} with small-sized Cu2O photocathodes, which could reach an STH conversion efficiency of 10% in an ideal tandem configuration, exceeding the NanoPEC target milestone. Crucially, they solved the inherent instability of Cu_2O by engineering 20nm thick protective overlayers of Al-doped ZnO and TiO_2. Furthermore, NanoPEC successfully scaled these photocathodes to a 63 cm² active area and achieved a record photocurrent of 3.3 mA cm^{-2} in nanostructured Fe2O3 photoanodes, demonstrating that this multi-component nanotechnology approach can effectively bypass the intrinsic bottlenecks of early materials [5].

• Fully artificial photo-electrochemical device for low temperature hydrogen production (ArtipHyction | 2012–2015 | €3,594,580.50)

Taking a biomimetic approach, this project sought to split water at ambient temperatures by developing an artificial device that mimics natural photosynthesis, specifically replicating the functions of the Photosystem II (PSII) enzyme and hydrogenase. To achieve this without relying on expensive noble metals, the project engineered a tandem photoelectrochemical system utilising a Mo-doped $BiVO_4$ photo-anode and molecular cobalt-based cathodic electro-catalysts. ArtipHyction achieved a historic scale-up milestone, transitioning from 1.5 cm² lab-scale cells (which demonstrated up to 5% solar-to-hydrogen efficiency) to a massive 1.6 m² modular proof-of-concept prototype, elevating the technology to TRL 5. Proving its long-term viability, the final prototype module comprising 5 PEC-PV units was tested for 1,000 continuous hours, successfully producing ~1 g/h of H2 at a 2% solar-to-hydrogen (STH) efficiency, with a performance reduction of less than 5% [6].

• Photoelectrochemical Demonstrator Device for Solar Hydrogen Generation (PECDEMO | 2014–2017 | €3,337,682.79)

Aiming to transition basic materials into scalable functional prototypes, this project developed hybrid photoelectrochemical-photovoltaic (PEC-PV) tandem devices utilising low-cost metal oxides (Fe_2O_3, $BiVO_4$, Cu_2O) coupled with silicon or perovskite PV cells. The project set three primary targets: 10% solar-to-hydrogen (STH) efficiency, 1,000 hours of stability, and a 50 cm² active area. While meeting all three simultaneously in a single system remains a challenge, PECDEMO successfully achieved each target individually. It reached an outstanding 16.2% STH efficiency in small-area devices using a Ga_2O_3/Cu_2O nanowire photocathode paired with a silicon PV cell. For scalability, it achieved an unprecedented 3.5 mA/cm² photocurrent on a

50 cm² Cu_2O photoelectrode, while its Fe_2O_3 components demonstrated exceptional durability with negligible performance loss after 1,000 hours of operation. At the system level, optimised designs successfully kept cell temperatures below 55°C under intense 17-suns concentrated light, though field tests of a modular 50 cm² array revealed that $BiVO_4$ and Fe_2O_3 components yielded modest efficiencies under these concentrated conditions due to poor carrier transport. Crucially, PECDEMO pioneered major conceptual architectural breakthroughs, including a power management scheme for the simultaneous co-generation of electricity and hydrogen, and the use of auxiliary $NiOOH/Ni(OH)_2$ electrodes to avoid the need to separate H_2 and O_2 within the same cell [7].

3.2 Second-Generation Leap: Industrial & Large-Scale Solar-to-X Systems

As fundamental materials matured, European funding transitioned toward scaling these technologies to industrial, multi-megawatt capacities

- **The HYDROSOL Lineage (2010–2024 | Total Investment: ~€8,180,000)**

Serving as the European benchmark for industrial scale-up, this lineage advanced two-step concentrated solar power (CSP) thermochemical water splitting across three continuous funding cycles. Instead of mixing their achievements, their technological evolution was viewed chronologically:

I. HYDROSOL-3D (2010–2012 | €1,729,084.60)

Transitioning from early 100 kW proofs of concept, this phase successfully finalised the complete pre-design and kinetics for a 1 MWth solar demonstration plant. Through techno-economic analysis, the project found that adapting an existing solar tower platform for hydrogen production is approximately 3 times cheaper than constructing a new plant from scratch [8].

II. HYDROSOL-PLANT (2014–2018 | €3,453,422.16)

This project turned the 1 MW blueprint into hardware by erecting a 750 kWth pilot plant, the largest demonstration facility of its kind worldwide. It featured three massive 90 L cavity reactors (250 kWth each) and successfully scaled up the synthesis of active NiFe2O4 redox material to 15 kg/day. At the laboratory scale, it proved exceptional durability by operating NiFe2O4 structures for over 1,000 consecutive cycles without failure. However, during field operations, optical component failures and thermal limitations (operating at 950–1000°C rather than the optimal 1100°C/1400°C) resulted in the plant producing only 0.25 kg/week of H2, falling short of its 3 kg/week target. Laboratory extrapolations confirmed the plant *could* reach 2.8 kg/week if optimal temperatures were sustained [9].

III. HYDROSOL-beyond (2019–2024 | €2,999,940.00)

Focusing on removing final bottlenecks, this phase targeted a 5% field efficiency and 60% heat recovery. The consortium achieved a major hardware breakthrough by integrating a hybrid ceramic-metallic heat exchanger that successfully recovered 68% of the process heat on the solar platform. Despite maintaining H2 yields for >1,100 cycles at the lab scale, the final field demonstration yielded a ~2% solar-to-fuel efficiency [10].

• **Technology demonstration of large-scale photo-electrochemical system for solar hydrogen production (PECSYS | 2017–2020 | €2,499,992.50)**

Aiming to drive the levelised cost of hydrogen (LCOH) below €5/kg, this project focused on scaling integrated photo-electrochemical concepts from lab-scale prototypes up to a massive demonstrator exceeding 10 m². The project evaluated parallel concepts, including thermally integrated PV-alkaline electrolysers that successfully scaled silicon heterojunction modules from a 294 cm² to a 2600 cm² collection area. However, the major engineering breakthrough came from its directly coupled PV-PEM electrolyser concept, which pioneered a "minimised balance of plant" architecture. To drastically reduce costs and complexity, this system eliminated mechanical water pumps, power management electronics, and active heating or cooling, relying solely on hydraulics. Surpassing its initial baseline targets of a 6% solar-to-hydrogen (STH) efficiency and 6 months of stability, the consortium deployed a final 10 m² outdoor demonstrator array that operated continuously under real-world conditions for 9 months (2,680 hours). This massive, highly simplified system successfully produced 22 kg of hydrogen while maintaining an average STH efficiency of 10% with less than 10% relative degradation, demonstrating the viability of large-scale, robust solar H2 generation and prompting consortium plans for a 250-kW scale-up [11].

3.3 The Polygeneration Paradigm: The Path to SPECTRUM

While single-product energy generation systems are foundational to the energy transition, they often underutilise the full potential of the infrastructure they invest in. Transitioning to a polygeneration model maximises resource efficiency and unlocks multiple revenue streams. This paradigm shift paves the direct pathway for holistic architectures like the SPECTRUM project.

• **Acceleration of Photocatalytic Green Hydrogen Production to Market Readiness Through Value-Added Oxidation Products (PH2OTOGEN | 2024–2027 | €2,498,813.75)**

Aiming to validate the polygeneration paradigm and reach TRL 5, this project fundamentally redesigns solar hydrogen generation by replacing the traditional oxygen evolution reaction with glycerol oxidation. This innovation co-produces hydrogen gas alongside 1,3-dihydroxyacetone (DHA), an oil 50 times more valuable than glycerol, thereby eliminating explosive H2/O2 risks and enabling simple, membrane-free separation. Currently, the team has successfully scaled its proprietary transparent conducting porous support (TPCS) to 100 cm², increasing mechanical load-bearing capacity from 25 g to 135 g. Concurrently, lab-scale organic semiconductors have yielded >4 mA/cm² photocurrents for hydrogen evolution, while $BiVO_4$ components have reached 3.4 mA/cm² for DHA production. Ultimately, these optimised components will be integrated into a final 500 cm² scalable photoreactor demonstrator targeting a 5% solar-to-hydrogen efficiency, providing a highly lucrative dual-revenue pathway for market introduction [2].

• **GreenH2 production from water and bioalcohols by full solar spectrum in a flow reactor (GH2 | 2022–2026 | €2,201,654.72)**

Anchoring the polygeneration paradigm, this project bypasses the sluggish water oxidation half-reaction entirely by replacing it with biomass-derivative oxidation. Its core scientific breakthrough is capturing the full solar spectrum (300–2500 nm) by synergising solid Z-scheme

UV-visible photocatalysis with infrared-driven (IR) thermal catalysis in a continuous flow reactor. By targeting its distinct mechanistic targets separately, the project aims for a 60% quantum yield for light-driven hydrogen production, alongside >90% selectivity for high-value chemical co-production. Strictly partitioning early lab outcomes by light source: under UV-visible light, a novel catalyst derived from agricultural fertiliser achieved a remarkable 70% quantum yield for light-driven hydrogen production from ethanol, successfully surpassing its baseline metric. Concurrently, under pure IR irradiation (>700 nm), the flow reactor demonstrated a hydrogen production rate of ~4.5 mmol/h and a highly valuable acetaldehyde production rate of ~4.4 mmol/h, achieving the target ~90% selectivity. These rigorous, dual-spectrum metrics prove that polygeneration architectures can simultaneously maximise zero-emission energy yields and lucrative chemical output [12].

- **Thermochemical Sulphur Cycles (SOL2HY2 & HySelect)**

Anchoring the high-temperature polygeneration approach, these linked projects advanced the hybrid sulphur (HyS) water-splitting cycle to efficiently co-produce hydrogen and valuable industrial chemicals.

I. Solar-to-hydrogen hybrid thermo-chemical cycles (SOL2HY2 | 2013–2016 | €3,727,404.20)

The SOL2HY2 project pioneered the breakthrough in primary polygeneration by validating the "Outotec Open Cycle." Instead of operating a closed chemical loop, this novel architecture deliberately co-produces commercial-grade sulfuric acid alongside hydrogen, a synergistic design that lowers H2 production costs by 50–75% while supplying a massive global acid market. Technically, SOL2HY2 successfully operated a room-temperature Sulfur Dioxide Depolarised Electrolyser (SDE) that eliminated the need for expensive platinum-group metal (PGM) catalysts by utilising gold-plated steel bipolar plates, effectively reducing stack costs by roughly three times compared to analogue PEM designs [3].

II. Efficient water splitting via a flexible solar-powered Hybrid thermochemical-Sulphur dioxide depolarised Electrolysis Cycle (HySelect | 2023–2026 | €3,982,105.00)

Building directly on this foundation, the ongoing HySelect project aims to drive this architecture toward a multi-megawatt Levelized Cost of Hydrogen (LCOH) below €5/kg. Its most interesting engineering innovation is physically decoupling the solar heat collection from the chemical reactor. Strictly separating completed past results from current operations: while SOL2HY2 demonstrated initial acid-cracking components, HySelect has now successfully installed a novel centrifugal particle solar receiver and a high-temperature hot-particle storage system at the Solar Tower Jülich. This advanced system is currently undergoing commissioning to enable a targeted 6-month continuous field demonstration, seeking to prove that hot-particle heat transfer can sustain uninterrupted, large-scale polygeneration even without direct sunlight [13].

- **Direct co-processing of CO_2 and water to sustainable multicarbon energy products in novel photocatalytic reactor (DESIRED | 2022–2026 | €3,058,752.50)**

Aiming to reach Technology Readiness Level (TRL) 4, this project develops an innovative oscillatory-flow photoreactor to directly co-process CO_2 and water into multicarbon (C_2–C_4) solar fuels and methanol for hard-to-abate sectors such as aviation. Pushing beyond traditional catalysts, the project achieved a major breakthrough by discovering that bio-sourced diatom frustules act as inorganic facet inducers for Cu_2O nanostructures, thereby allowing selective tuning of carbon-carbon coupling pathways. At the catalyst and electrode level, DESIRED developed multilayer Cu-oxide ($Cu_2O/Al_2O_3/TiO_2$) architectures that delivered a 2.8-fold higher photocurrent and up to 69% methanol Faradaic efficiency in seawater-compatible saline electrolytes, alongside a new family of hybrid inorganic-organic overlayers that double the incident photon-to-current efficiency (IPCE) and extend operational stability beyond 20 hours. Furthermore, the consortium successfully engineered a 450 ml level 2 dual-compartment reactor equipped with a novel hybrid specular-diffuse reflector that improves optical efficiency by >15% [14].

- **Solar Energy for Carbon-Free Liquid Fuel (Sun-To-X | 2020–2024 | €3,096,643.75)**

Cementing the circular-economy approach to polygeneration, this TRL 4 project developed HydroSil, a zero-emission silicon-hydride liquid fuel that dual-functions as transportable energy storage and a highly reactive chemical agent for upcycling waste plastics. Strictly separating hardware and chemical achievements: the consortium first developed a patented transparent porous substrate (fluorine-doped tin oxide-coated quartz felt) to extract hydrogen directly from ambient humidity, then scaled these photoelectrodes from >100 cm^2 to a nine-module tandem device with a massive ~900 cm^2 active area. Concurrently, on the chemical side, the team demonstrated HydroSil's polygeneration recycling capability by leveraging its Si-H bonds and optimised catalysts to achieve an outstanding >95% conversion of polycaprolactone (PCL) plastic waste into highly valuable hydrocarbons, including 1,6-hexanediol. These exact metrics rigorously prove that novel solar architectures can simultaneously drive carbon-free liquid fuel synthesis and highly selective chemical recycling [15].

- **Standalone solar-to-X device for prosumer-oriented conversion of sunlight to Ethene and Ammonia (SOLEAS | 2025–2029 | €3,836,135.51)**

Targeting Technology Readiness Level (TRL) 5-6, the SOLEAS project aims to develop a standalone, multi-product photoreactor to simultaneously synthesise ethene (C_2H_4) and ammonia (NH_3) directly from water, biogenic CO_2, and atmospheric N_2. By bypassing intermediate hydrogen chains, this system will provide a self-sufficient, decentralised solution for the localised "prosumer" model. To maximise performance, the reactor architecture will integrate breakthrough concentrator optics, quantum-dot wavelength adjustment, a zero-gap design, and optimised fluid dynamics. Furthermore, SOLEAS aims to meet strict commercial benchmarks, including Solar-to-X efficiencies>12.5%, Faradaic efficiencies >70%, and specific productivities of up to 0.5 $kg/m^2{\cdot}hr$ for ammonia and 0.2 $kg/m^2{\cdot}hr$ for ethene. Ultimately, this technology is expected to guarantee a substantial environmental impact, avoiding over 1.9 tons of fossil-derived CO_2 emissions per ton of product [16].

4. The Ultimate Synergy: Full-Spectrum Harvesting & Dynamic Architectures (the SPECTRUM Vision)

The entire historical trajectory of European energy funding from the material discovery of NanoPEC to the large-scale outdoor deployment of PECSYS and the co-product economics of PH2OTOGEN logically converges on a single target. The future demands a single system that achieves full-solar-spectrum thermodynamic utilisation and complete multi-vector polygeneration. This is the exact vision championed by the SPECTRUM framework, which synthesises the fragmented breakthroughs of previous EU projects into a single unified architecture.

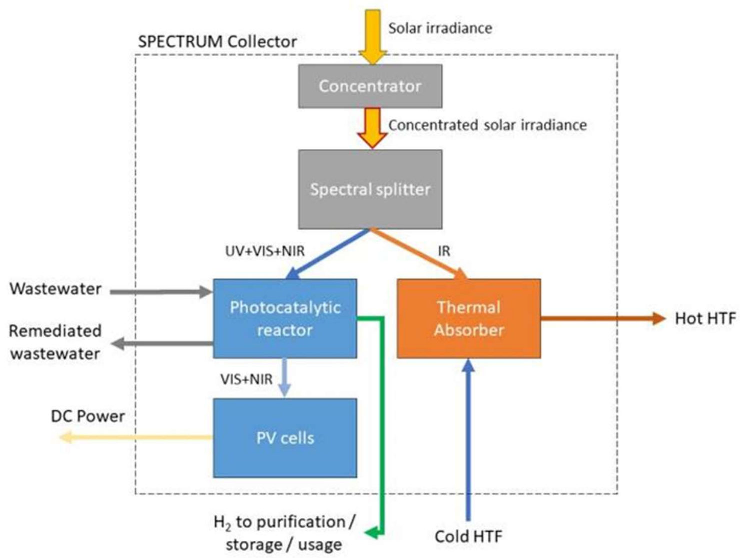

Figure 2 SPECTRUM general concept [1]

As illustrated in Figure 2, this unified architecture relies on five main subsystems: an optical concentrator, a spectral splitter, a thermal absorber, a photocatalytic reactor, and a photovoltaic (PV) module. Incoming solar irradiance is first captured by the concentrator and directed to the spectral-splitting layer, which divides the light into distinct optical fluxes that perfectly match the energy grades required by each component. The infrared (IR) radiation is routed directly to the thermal absorber, heating a cold Heat Transfer Fluid (HTF) to supply high-temperature industrial heat. The UV and near-UV VIS are absorbed by a mixture of wastewater and photocatalysts, driving photocatalytic degradation of pollutants with the cogeneration of H_2. The remaining VIS and near-infrared light will be converted into electricity by photovoltaic cells [1]. The final design of the SPECTRUM collectors will be implemented in two different configurations, each operating at different concentrating factors and temperatures, to be tested in outdoor conditions with different industrial wastewaters and tailored catalysts.

4.1 Full-Spectrum Polygeneration and Co-product Maximisation

Traditional Solar-to-X plants suffer severe efficiency limits because they capture only a fraction of incoming light wavelengths. The GH2 project demonstrated that capturing the full solar spectrum by coupling UV-visible photocatalysis with infrared-driven thermal catalysis in a flow reactor can achieve a targeted hydrogen quantum yield of 60% [12]. SPECTRUM advances on this concept by converting the full solar spectrum into three distinct energy vectors: solar heat, solar electricity, and green. As mentioned, rather than forcing all wavelengths into a single chemical reaction, SPECTRUM maximises co-product generation by dedicating each specific waveband to its most thermodynamically efficient process, as discussed earlier. This ensures that no photon is wasted, allowing the system to simultaneously maximise its three distinct energy vectors while avoiding the severe efficiency drops that plague traditional single-product plants [4].

4.2 Turning Thermal Disadvantages into System Synergies

A major challenge in highly integrated Solar-to-X systems is the thermal penalty: PV panels lose up to 20-30% of their electrical efficiency when they overheat [1]. The earlier PECSYS project addressed this by directly coupling the PV and electrolyser, demonstrating that in hot environments, accelerated electrochemical reaction kinetics could overcompensate for reduced PV conversion efficiency [11]. While PECSYS accepted hot PV cells as a necessary trade-off for better chemistry, SPECTRUM will try to eliminate or at least limit this compromise. By utilising the spectral splitting (SS) solution introduced above, SPECTRUM can physically and thermally decouple the PV cells from the thermal absorber. Because the PV cells are isolated from the intense heat generated by the infrared radiation, they remain cool and operate at peak electrical efficiency. This decoupling allows SPECTRUM to maximise both electrical and thermal output simultaneously without forcing a system-level trade-off [1].

4.3 Transforming Waste into a Valuable Chemical Feedstock

Traditional photocatalytic H_2 production faces economic barriers because it requires expensive "sacrificial agents" (like pure methanol) to work efficiently. SPECTRUM solves this by using industrial wastewater (IWW) for photocatalysis. The organic pollutants in the wastewater act as the sacrificial agents. This dual-functional photocatalysis degrades the pollutants while simultaneously boosting H_2 generation [1].

4.4 Bridging Control and Downstream Gaps

As systems become highly integrated and multi-vector, managing transient solar inputs becomes incredibly complex. SPECTRUM bridges this by adopting dynamic control and modelling philosophies, as in HySelect (subsystem requirements for solar platform testing) and GreenHyScale (WP3 automated multi-physics control platforms) [1], [13], [17]. Crucially, SPECTRUM extends this philosophy by tightly coupling lab-scale experimental testing with industrial-scale process simulation. Data gathered from the operation of lab-scale prototypes under outdoor conditions will be fed directly into comprehensive computational models utilising tools like ASPEN and MATLAB-Simulink. These multi-scale simulations model the complete integration of the SPECTRUM system into actual industrial energy and wastewater flows, enabling verification of operating profiles and annual yields before full-scale deployment. Furthermore, SPECTRUM looks ahead to real-world integration by aligning its structural safety with downstream logistics, applying Model Predictive Control (MPC) algorithms and ATEX safety classifications to build an economically viable and fully certified energy hub [1].

5. Conclusion

The historical evolution of EU-funded Solar-to-X research demonstrates that the future of industrial decarbonization does not lie in single-product, monolithic energy plants. Early framework programs successfully resolved foundational material and electrochemical bottlenecks, while subsequent initiatives proved the feasibility of megawatt-scale solar towers and field arrays. However, the real-world deployment of standalone solar-to-hydrogen systems remains severely hindered by low isolated exergy efficiencies, intense land competition, and unfavourable standalone economics.

The true path to market readiness lies in high-density, multi-vector polygeneration hubs that maximise every fraction of the solar spectrum while integrating directly into industrial circular economies. The SPECTRUM framework synthesises decades of European innovation into a single, cohesive architecture. By employing advanced spectral splitting, SPECTRUM physically decouples photovoltaic cells from high-temperature absorbers, eliminating thermal penalties and enabling the concurrent generation of clean electricity, high-grade process heat, and green hydrogen.

Furthermore, by utilising industrial wastewater as a sacrificial electron donor for photocatalytic hydrogen evolution, SPECTRUM transforms a major environmental liability into a valuable solar fuel feedstock. This dual-functional remediation enables industrial facilities to comply with stringent regulations, such as the Urban Wastewater Treatment Directive (UWTD), while significantly reducing the levelized cost of hydrogen [1]. Coupled with multi-scale dynamic control models and downstream safety integration, this architecture bridges the gap between lab-scale innovation and commercial reality, establishing a transformative standard for decentralised, zero-emission industrial infrastructure.

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