Data-driven bottom-up demand-side management modelling towards integrated and smart renovation packages for efficient, sustainable, and inclusive energy use in real-life residential pilots across the European Union

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Introduction & Problem statement (1/3)

Buildings are accounting for nearly **40%** of final **energy consumption** in the EU.

50 million consumers struggle to keep their homes **adequately** warm.

Annual renovation rate of the building stock varying from **0.4** to **1.2%**.

More than **220 million building units**, representing **85%** of the EU's building stock, were built **before 2001**.

85-95% of the buildings that exist today will still be standing in 2050.

The building sector has significant room for decarbonisation.

Need for increased energy efficiency renovation efforts

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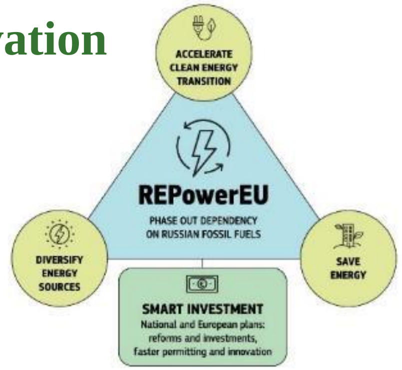
INTRODUCTION & PROBLEM STATEMENT (2/3)

Towards the uptake of energy efficiency in the building sector

- **Renovation Wave,** as part of the **EU Green Deal,** aims to **double** the annual energy **renovation rate** by 2030.
  - Aim to renovate **35 million inefficient buildings** by **2030**.
- **Fit For 55** sets a target of **reducing emissions** by at least 55% by **2030.**
- **REPowerEU** changes the future of **fossil fuel** use in buildings radically aiming to enhance efforts on **saving energy**, **diversifying energy supplies** and **producing clean energy.**



INTRODUCTION & PROBLEM STATEMENT (3/3)

EU lags behind the ambitious decarbonisation goals set by 2050, due to various barriers:

- **Financial Constraints, Split incentives**
- **Fragmented decision-making processes**
- **Uncertainty of long-term benefits of renovation investments**

Need to design, demonstrate, validate, and replicate integrated renovation packages for the efficient, sustainable and inclusive energy use.

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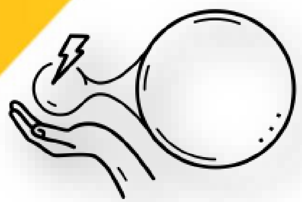
In this context, it's necessary to..



Design, demonstrate, validate and replicate **innovative renovation packages** to promote **Efficient, Sustainable and Inclusive Energy (ESIE)** in the building industry.

How?

- **Creation** of collaborative and innovative **business models.**
- Incentivisation and **behavioural change** models.
- Incorporation of a **digital currency**, **green-euro**, (€G).
- **Mapping** and **understanding** the **complex interplay** between the different stakeholders.

- **Energy use**
- **CO_2 Emissions**
- **Comfort**

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OUR APPROACH

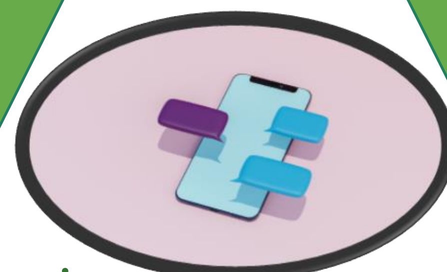
Constitute Green-Euro as a retail Central Bank Digital Currency (CBDC)

Innovative renovation financing approaches

Online marketplace, (One-Stop-Shop) offering advice

Direct contact with consumers through the value chain of stakeholders

Facilitate access to “packaged” renovation services



Collective narrative and **rewards**

Gamified app user interaction and continuous **motivation** through an **easy-to-understand visualisation**

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RESEARCH OBJECTIVES

Contribute to the development of innovative financial means and business models:

- ✓ Provide robust **data-driven insights** and **quantifications** on the impacts of different **renovation packages**.
- ✓ Identify **solutions** adaptable to **diverse contexts** and expedite their **replication** across the **EU**.
- ✓ **Enable** relevant stakeholders to assess the **economic viability**, **energy savings potential** and **environmental impact** of different renovation packages.
- ✓ Outcomes that facilitate **well-informed policy and decision-making.**
- ✓ Overcome **barriers** to the acceleration of the **Renovation Wave** and the achievement of **EU decarbonisation goals**.

Use data from installed sensors
AI and data-driven techniques

Employ Social Sciences and Humanities approaches for holistic engagement

Provide simulation data, "predict" what will happen in different future scenarios- recommendations to optimise renovation impacts

Compare and validate after the renovation is carried-out

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How are the Research Objectives Met?

Dynamic High-Resolution Demand-Side Management Model

Integrated renovation packages

Different **portfolios** of targeted **measures** & **financing options** per building typology under study

- ✓ **Analyse** the **cost-effectiveness** of **different portfolios** of **measures** and **financing schemes in the real-life pilots** under study.
- ✓ **Evaluate** the **performance** of **different conventional measures** in terms of their **long-term savings.**
- ✓ **Focus** on aspects of **energy poverty** and **assessment** of the **economic benefits** of each measure at a **disaggregated** level.
- ✓ **Inclusion** of measures that **improve demand-side management** and optimal control of **heating, ventilation, and air-conditioning systems**.

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The Model

TL DREEM

Dynamic High-Resolution Demand-Side Management Model

Building sector

Energy demand *simulation model*

Benefits *&* ***limitations*** *of demand-flexibility primarily for* ***consumers*** *& other* ***power actors*** *involved*

ELSEVIER

Energy Conversion and Management

Volume 205, 1 February 2020, 112339

A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector

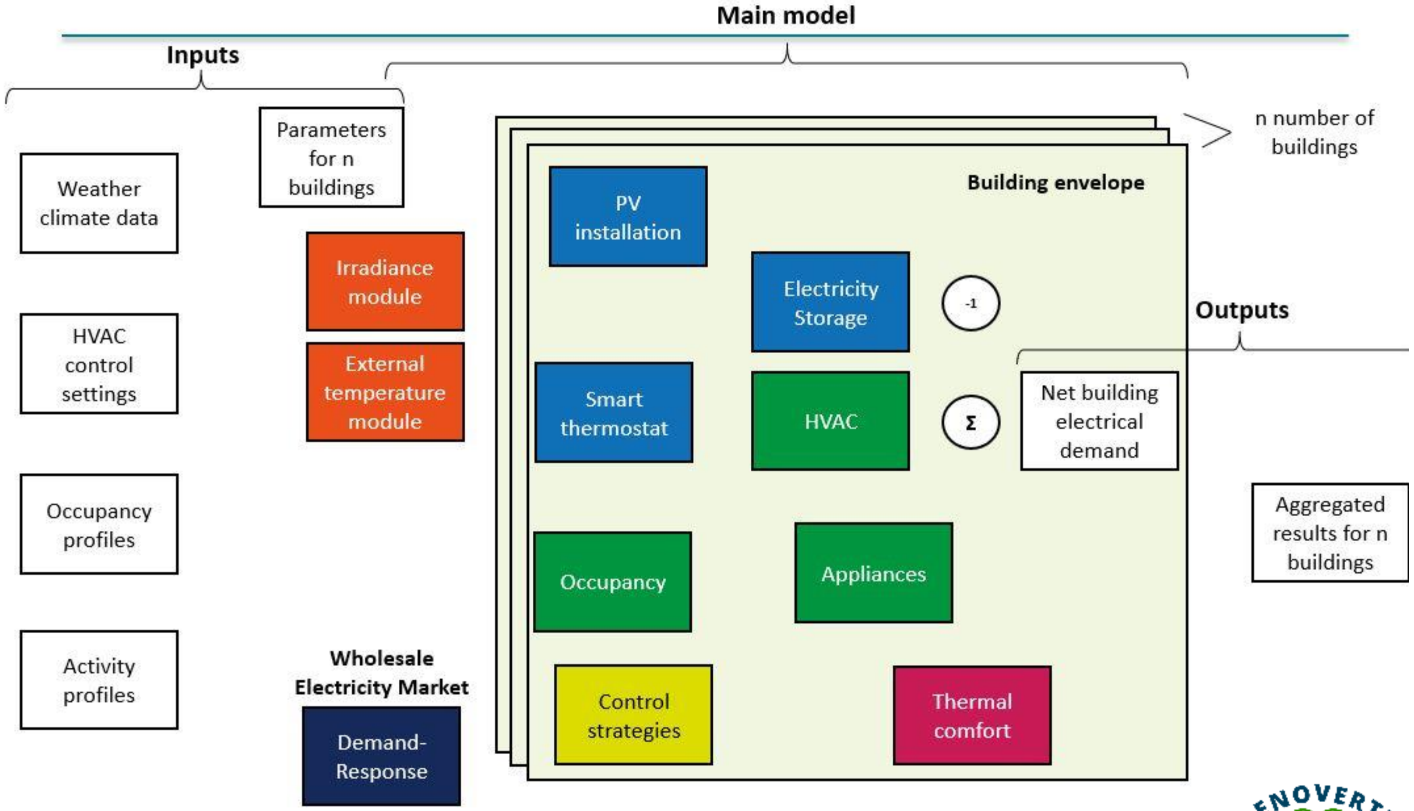
Vassilis Stavrakas, Alexandros Flamos

Currently applied and further developed in ***multiple EC-funded H2020****,* ***HE****, and* ***LIFE*** *projects*

MODEL CHARACTERISTICS (1/2)

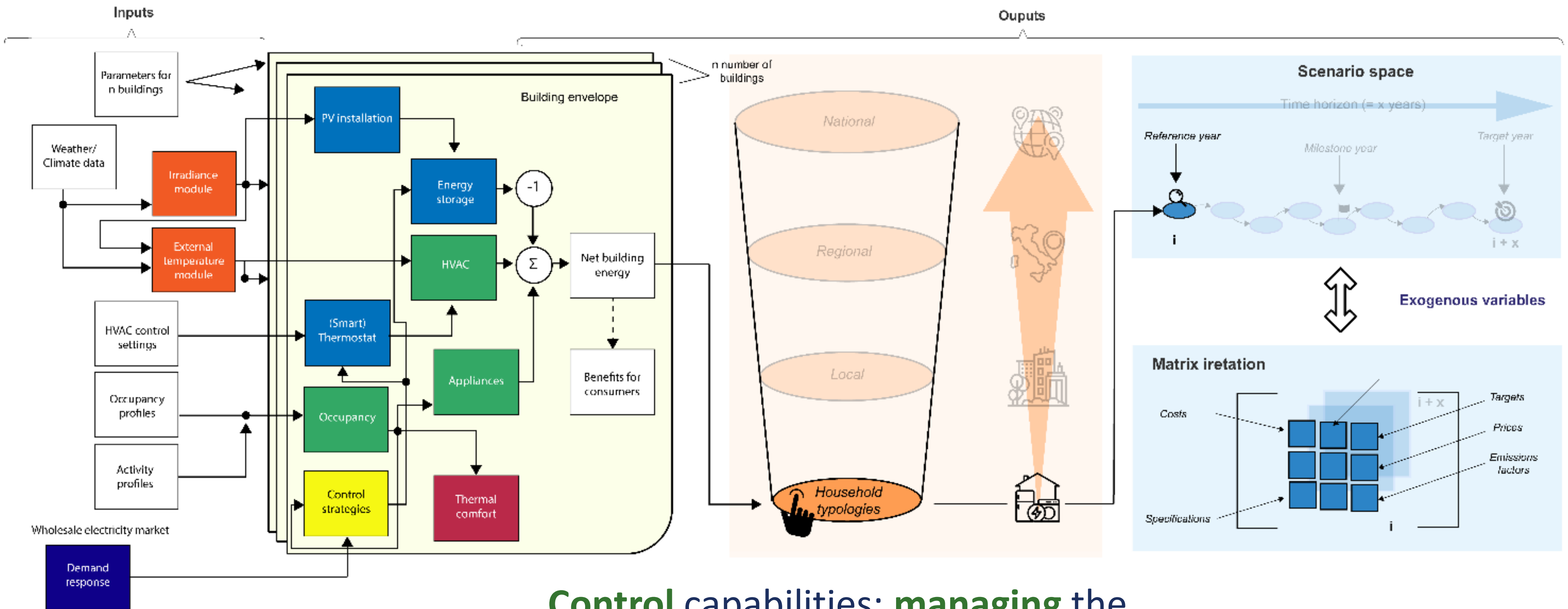
Main **principles** of **component-** & **modular-**based system modelling approach

- **Interdependence** of decisions **within** modules
- **Independence** of decisions **between** modules
- **Hierarchical dependence** of modules on components embodying standards & design rules



Modular *structure*

Model Characteristics (2/2)



✓ **Control** capabilities: **managing** the **complexity** of large systems/ simulation at **different levels**

✓ Fast development & simulations: **computational efficiency**

✓ **Realistic representations** of dynamic systems

How is the model employed in this application?

(e.g., necessary inputs, incorporation to the model and interaction between them)

Model Parameterisation (1/4)

Weather-Climate data

Climate.OneBuilding.Org

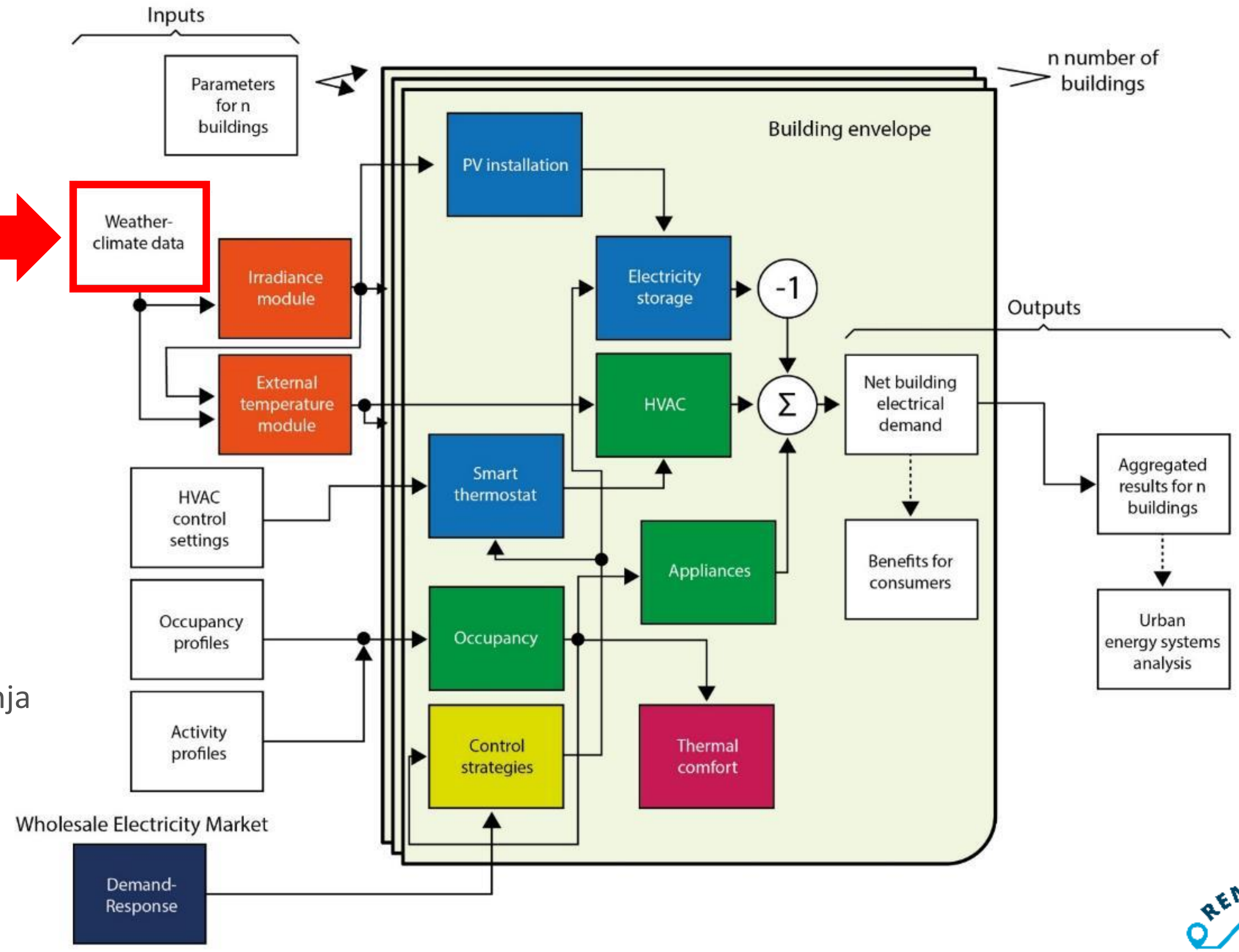
WMO

EnergyPlus

Copernicus Europe's eyes on Earth

Renewables.ninja

Typical Meteorological Years (**TMY**) for **several regions** in the **pilot** countries.



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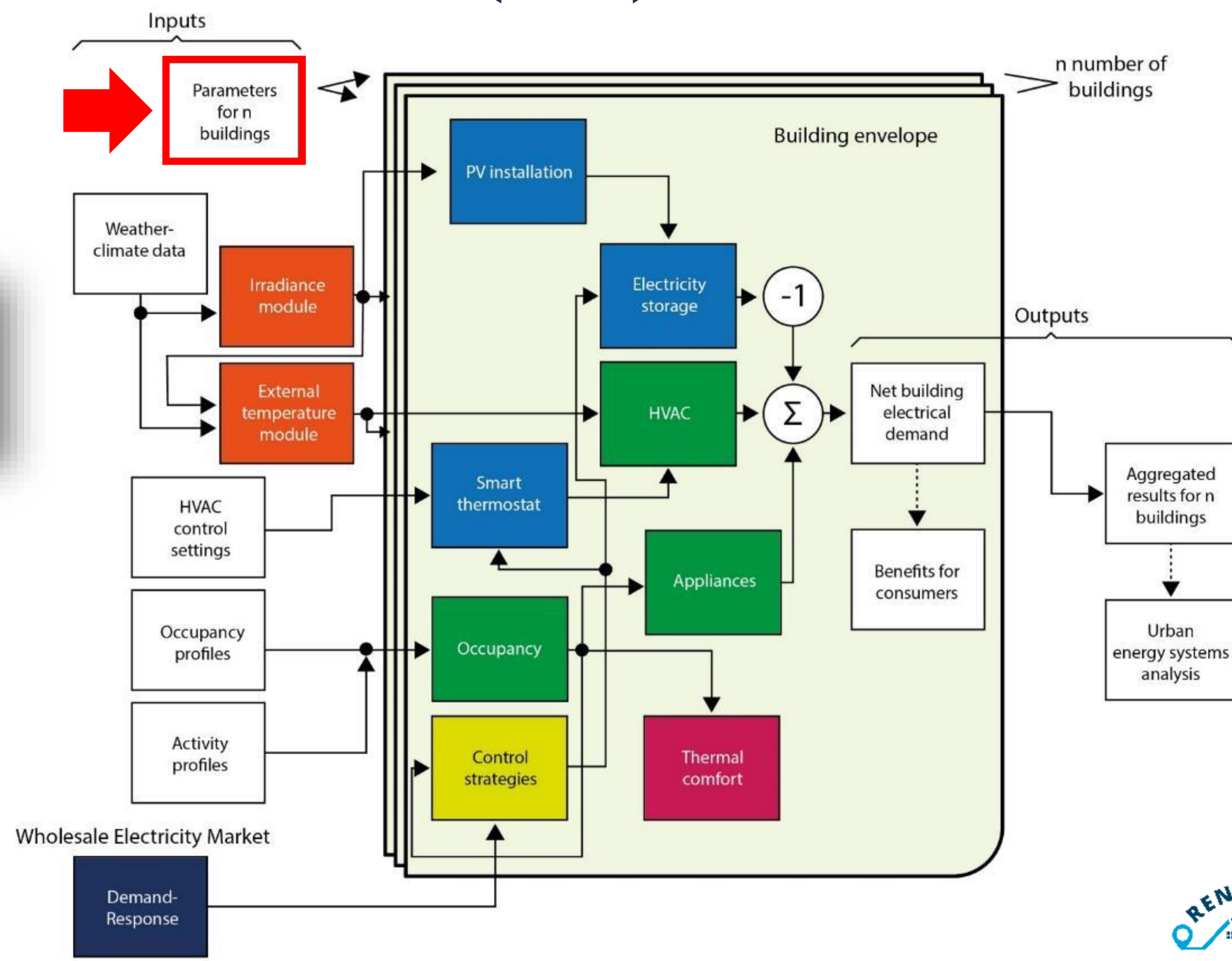
MODEL PARAMETERISATION (2/4)

Building parameters

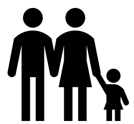
→ Use of real-life pilot data from the experts working/ following each pilot case

Construction year
Type of building
No. of floors
Total floor area, Height
Total roof area
Total walls area
Total windows area
U-values

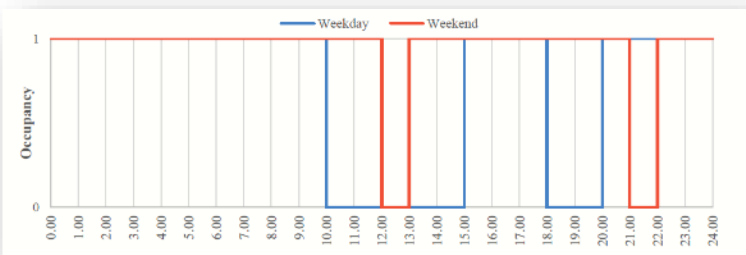


Model Parameterisation (3/4)

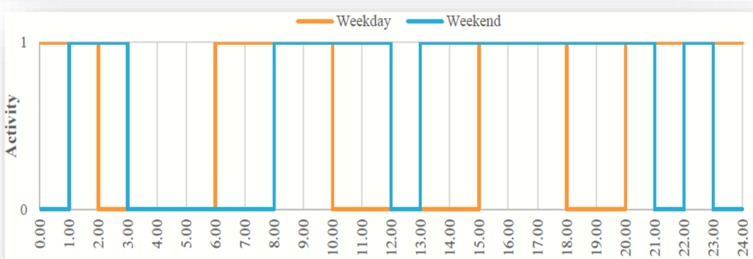
Occupancy & activity profiles



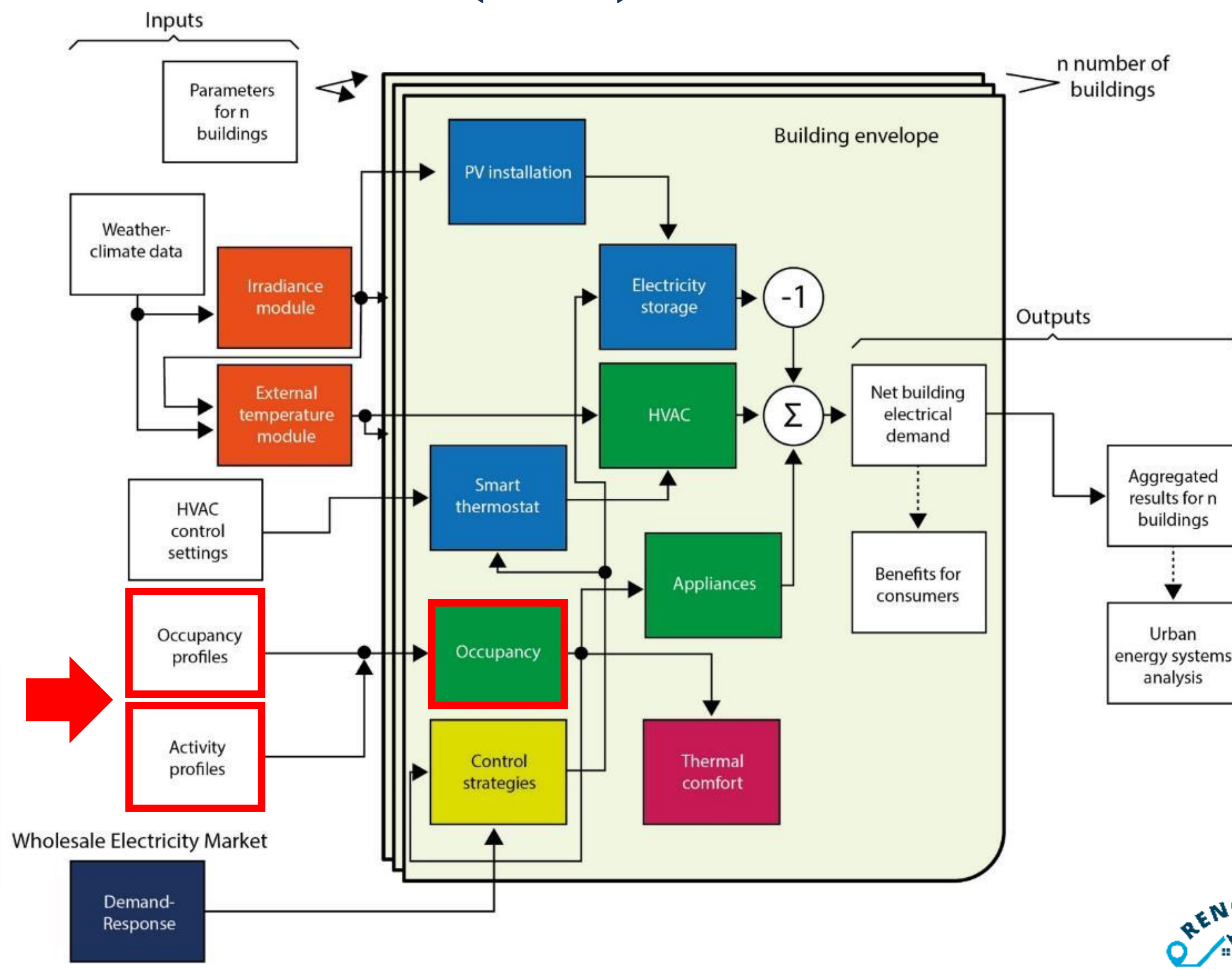
Building composition, occupancy & activity patterns



1= “at home”, 0= “not at home”



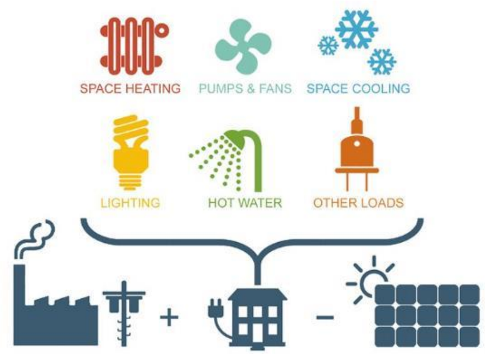
1= “active”, 0= “not active”

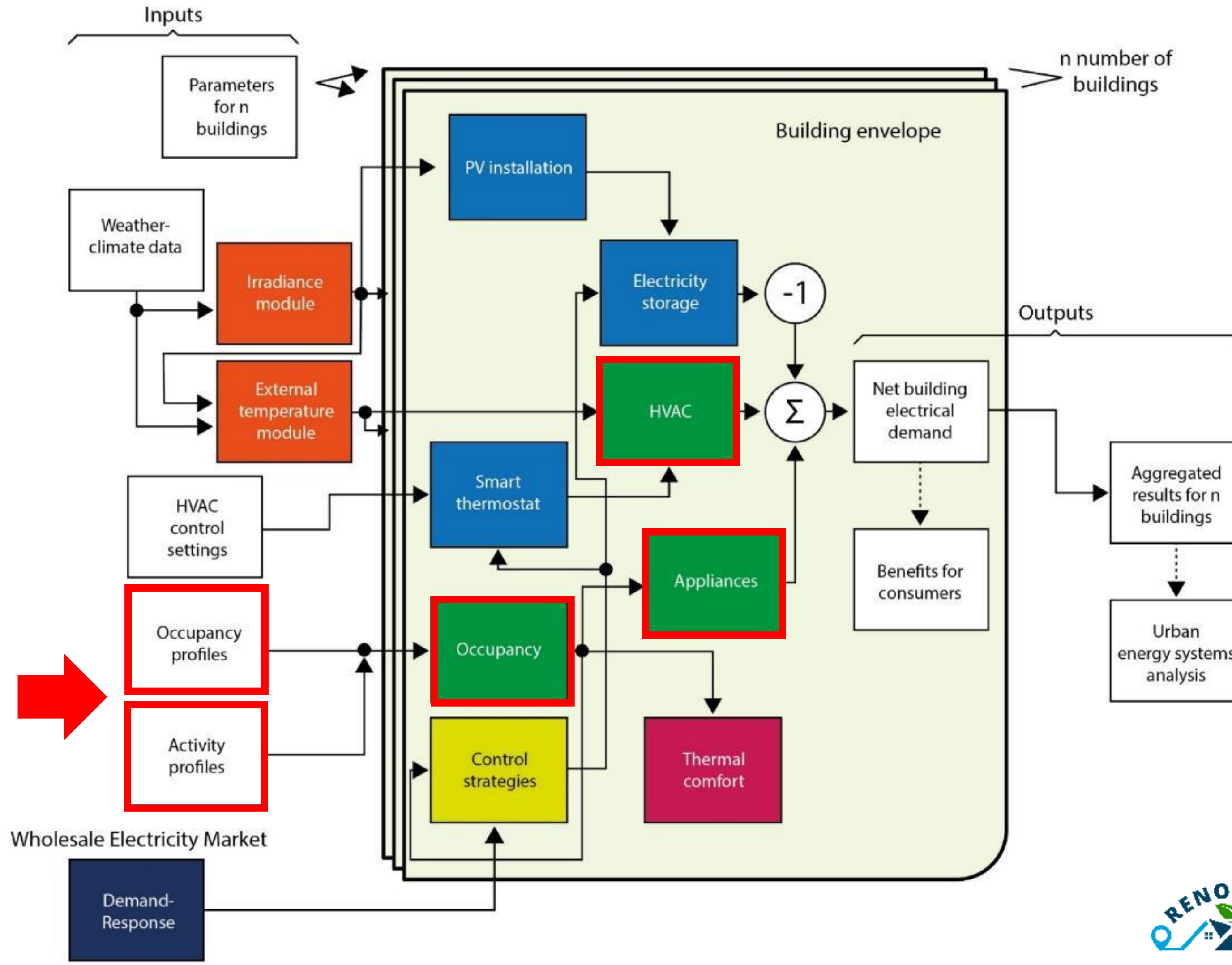


Model Parameterisation (4/4)

Occupancy & Activity profiles

HVAC & Appliance
ownership/use



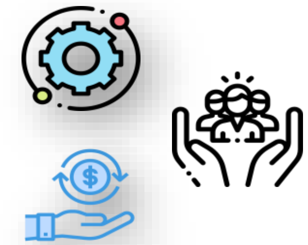


How are future situation scenarios formulated and evaluated?

Future situation Scenarios (1/3)

Evaluate the **performance** & **replicability** potential of **conventional Energy Efficiency Measures (EEMs)**

- ✓ Long-term energy savings
- ✓ Sustainability
- ✓ Risk
- ✓ Return of investment



Cost-effectiveness

$$LCSE = \frac{(CRF * \text{Cost}_{investment}) + \text{Cost}_{O\&M}}{Energy\ Svings\ (kWh)}$$

Heating technology change:

Substitution of fossil fuel boilers with efficient & **environmentally friendly** technologies (e.g., **heat pumps**, etc.)

★ assessing **benefits** of each measure at a **disaggregated** (households-neighbourhood) level

particularities of energy poor households

customer profiles

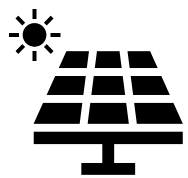
★ providing **investors, consumers** & other potential **end-users** with useful insights

FUTURE SITUATION SCENARIOS (2/3)

Evaluate the **performance** & **replicability** potential of **smart (EEMs)**

- ✓ Long-term energy savings
- ✓ Sustainability
- ✓ Risk
- ✓ Return of investment


Towards the **Smart-Grid** paradigm & **innovative policy** and **financial** frameworks



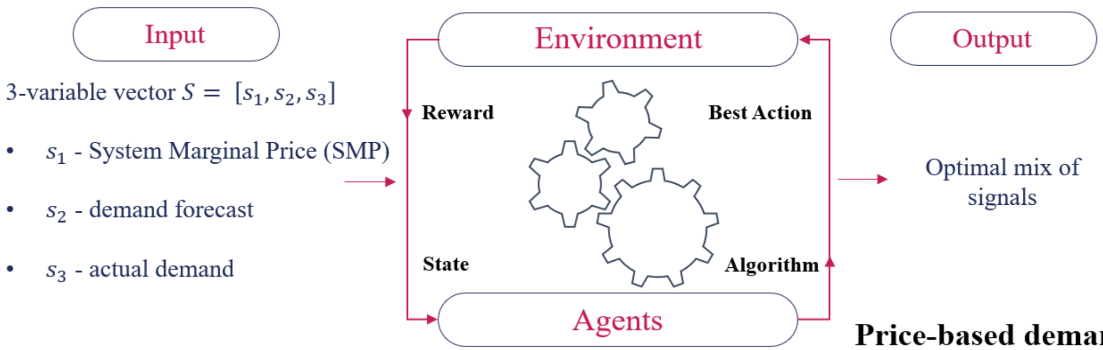
Prosuming & Storage

FUTURE SITUATION SCENARIOS (3/3)

Demand-response

Algorithms that illustrate the **decision-making** framework and **solve** the dynamic pricing problem considering both service provider's profit and consumers' costs.

Electricity market



Utilities/ Retailers

python

Reinforcement learning algorithms

Price-based demand-response signals based on realistic market values

Thermal comfort

Appropriate indoor thermal conditions and temperature ranges according to **thermal comfort standards.**

DIN EN ISO 7730

ASHRAE 55

EN 15251

Category	Thermal state of the body as a whole		Explanation
	PPD (%)	PMV	
I	<6	-0.2 < PMV < +0.2	High level of expectation: recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick children, elderly persons, etc.
II	<10	-0.5 < PMV < +0.5	Normal level of expectation: used for new buildings and renovations.
III	<15	-0.7 < PMV < +0.7	Acceptable, moderate level of expectation: used for existing buildings.
IV			
(a)	<20	-1 < PMV < +1	Marginal level of expectation: values that should only be accepted for a very limited part of the day.
(b)	>20	PMV < -1 or PMV > +1	Inacceptable level of expectation: values outside the criteria for the above categories, that should only be accepted for a very limited part of the year.

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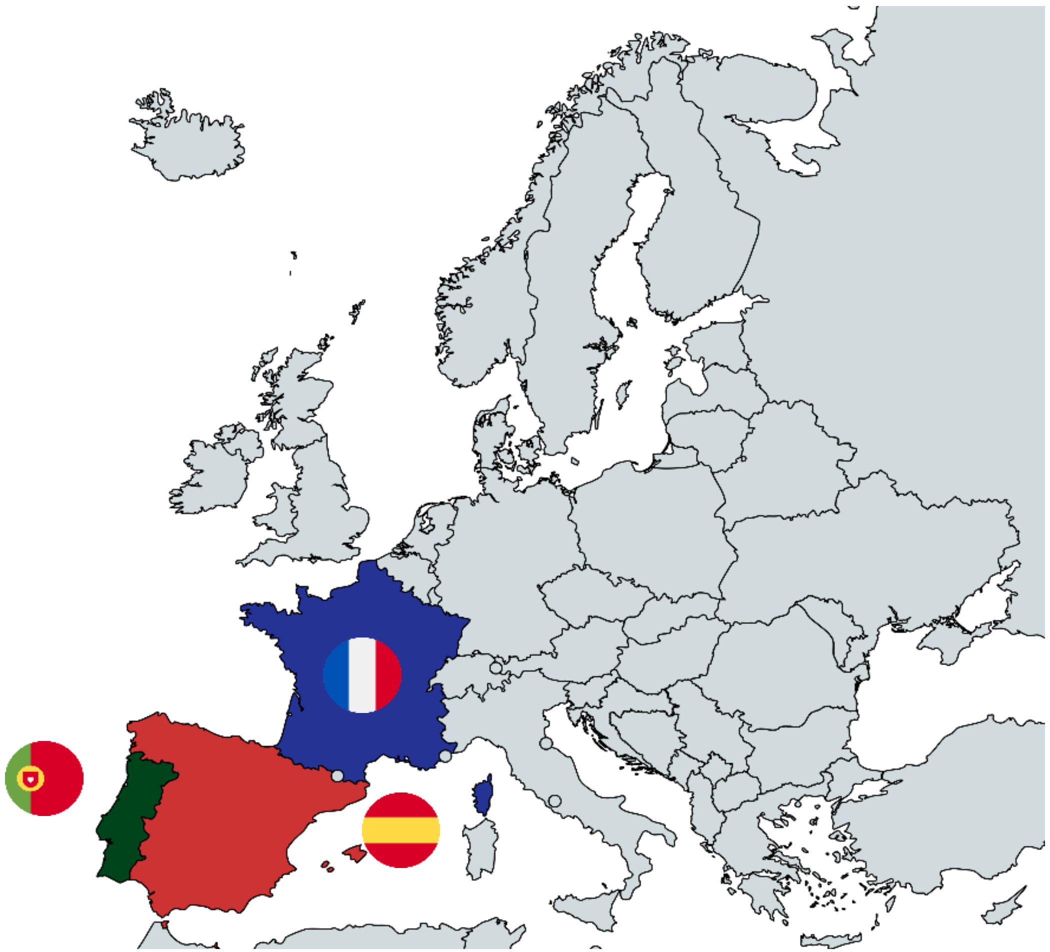
and finally….

What about the simulation process and results?

Chosen Pilot Cases



Results from 3 neighbouring countries (France, Portugal, Spain)

Meaningful to compare

Pilot case 3 - Portugal: Specifications

Country: **Portugal**
Region: Torres Vedras

Type of building/usage: Single Family House

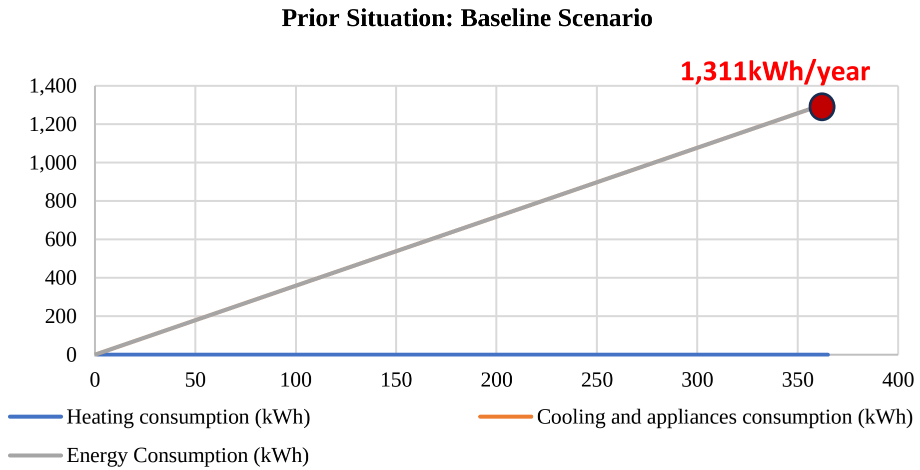
Year of Construction: 1955

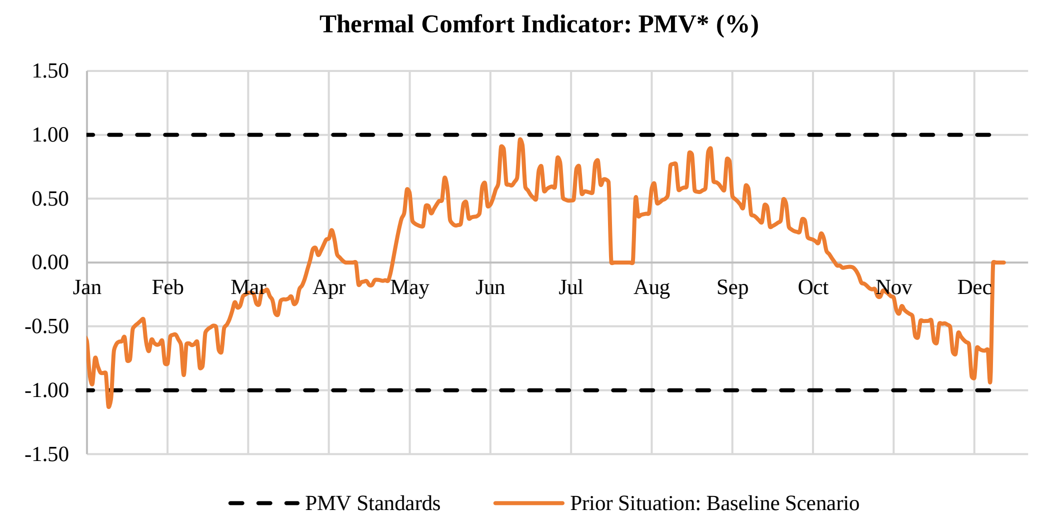
Building size: 1 Basement Level

Total floor area: $30m^2$

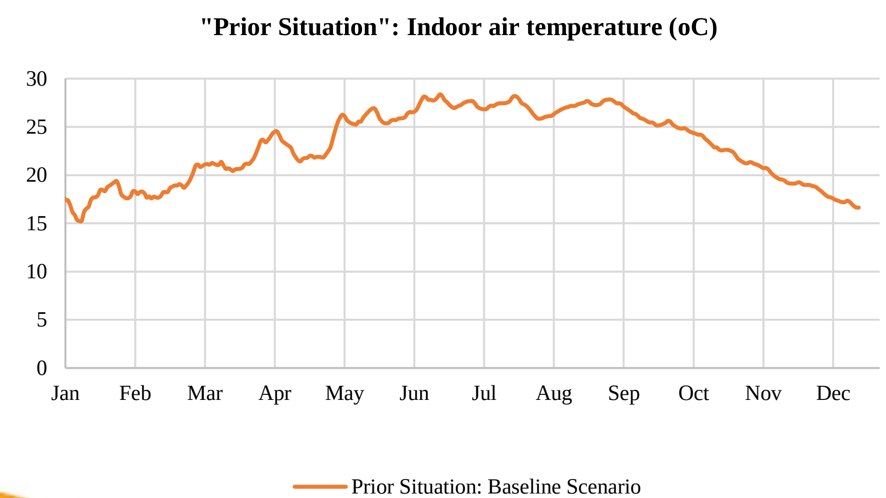
Prior Situation: Construction features (U-values)(W/m²/K)	
Uwall:	1.80
Ufloor:	1.00
Uroof:	0.99
Uwindow:	4.33
Prior Situation: Existing Building systems	
Heating system:	non existent
Nominal capacity:	non existent
COP (if available):	non existent
Cooling system:	non existent
Nominal capacity:	non existent
EER (if available):	non existent
Lighting equipment:	4 simple ceiling lamps and 3 table lamps
Lighting equipment capacity:	traditional 50W lamps
Future situation scenarios: Measures to be modelled	
Heating system change/upgrade	Heat Pump to provide hotwater and Hvac to heat the air
Cooling system change/upgrade	Hvac
Building envelope upgrades	Thermal Insulation with ETICs, Insulation in roof area, replacing windows for double glazed with thermal break
Upgrade of lighting system	Replacing all the bulbs with LED lightning
Smart systems	Solar panel installation
Thermal comfort according to standards	Yes

Pilot case 3 - Results: Baseline scenario





Torres Vedras



***Acceptable ranges of the Predicted Mean Vote (PMV): -1<PMV<1**

Thermal comfort indicator close to the **marginal prices**!

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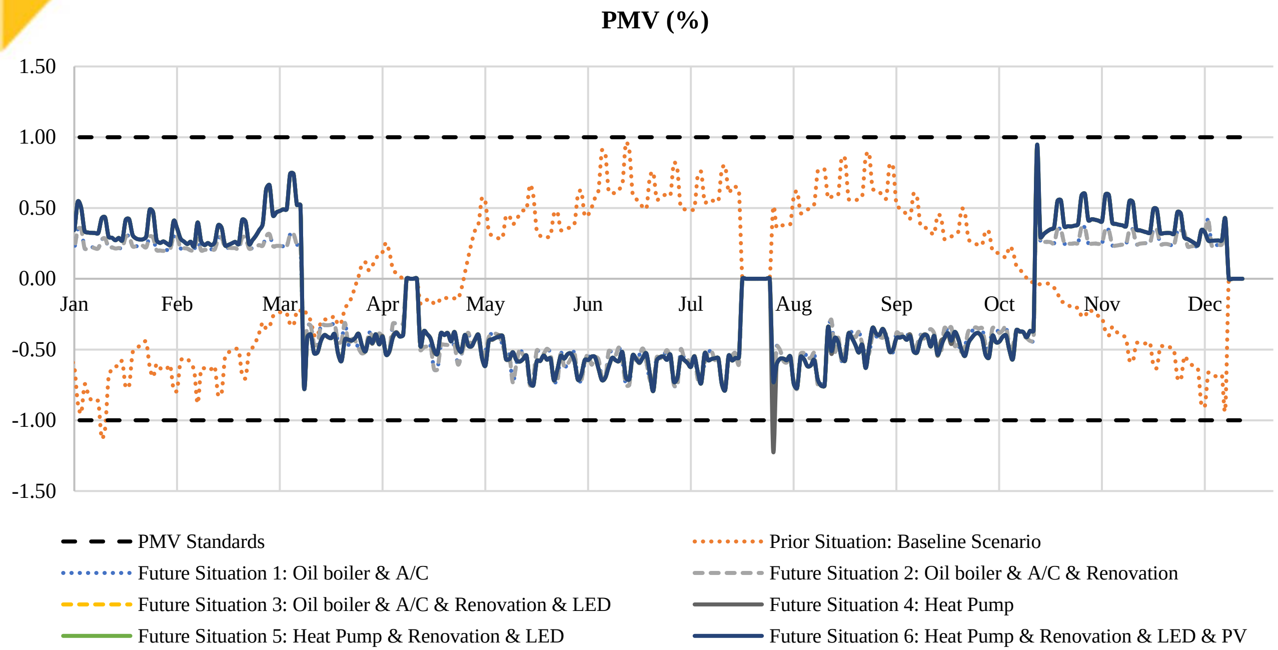
Pilot case 3 Results - Future situation scenarios

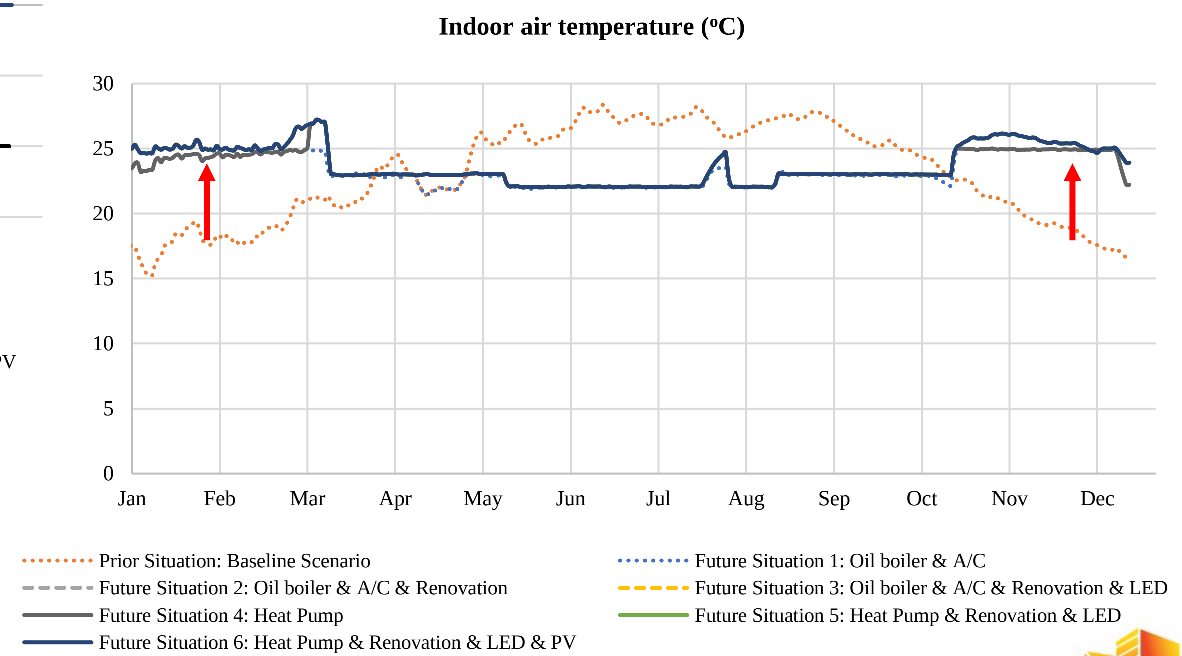
Future situation Scenarios	Energy efficiency measures implemented
1	Oil boiler & A/C
2	Oil boiler, A/C, Renovation (thermal insulation & windows upgrade)
3	Oil boiler, A/C, Renovation (thermal insulation & windows upgrade), LED lighting
4	Heat pump
5	Heat Pump, Renovation (thermal insulation & windows upgrade), LED lighting
6	Heat Pump, Renovation (thermal insulation & windows upgrade), LED lighting, PV installation

PILOT CASE 3 RESULTS: INDOOR CONDITIONS

Thermal comfort and internal conditions in the future situation scenarios



Warmer internal conditions in the winter!



Cooler internal conditions in the summer!

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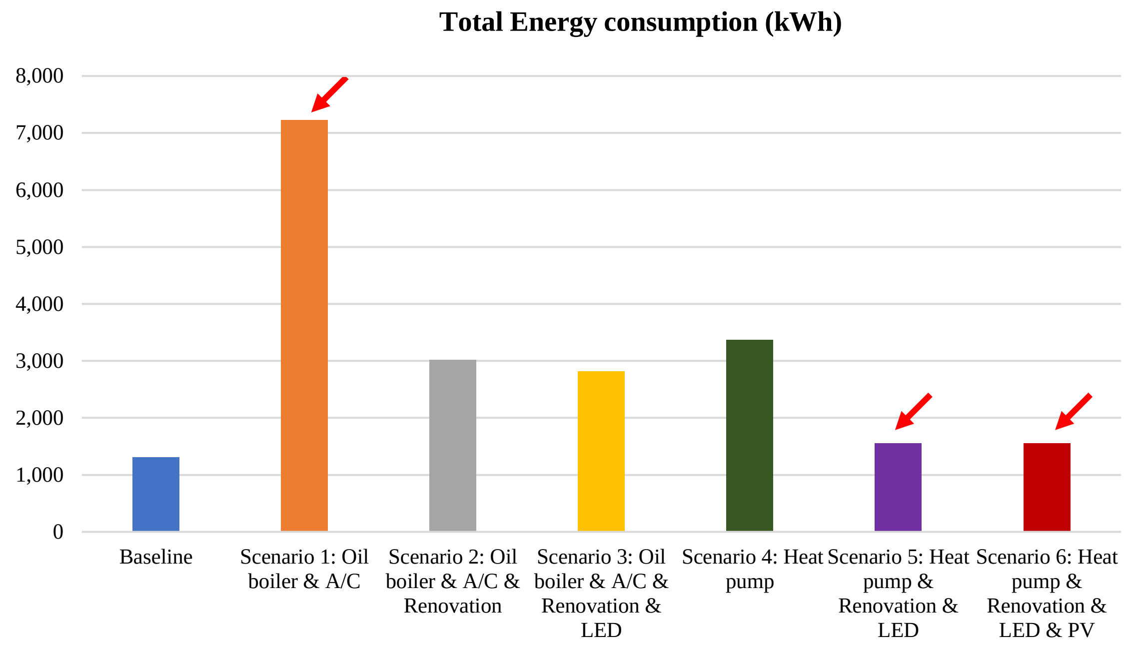
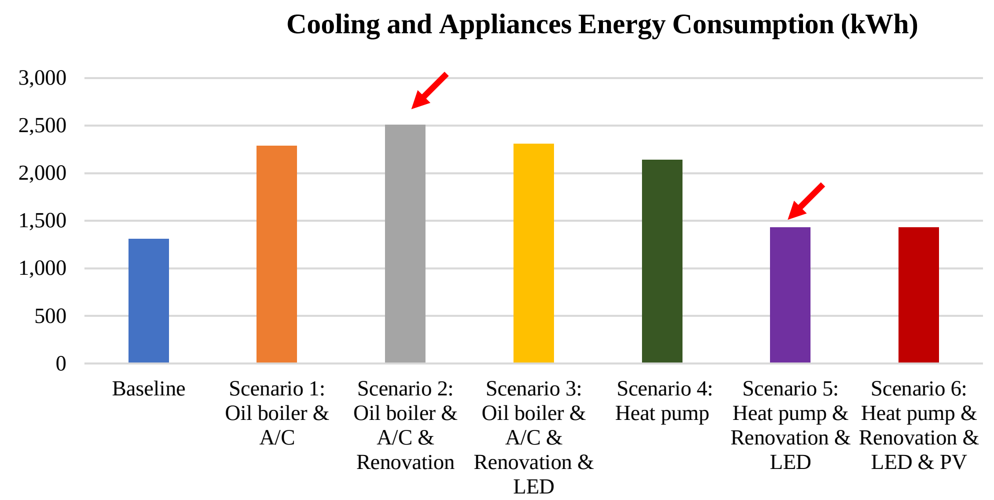
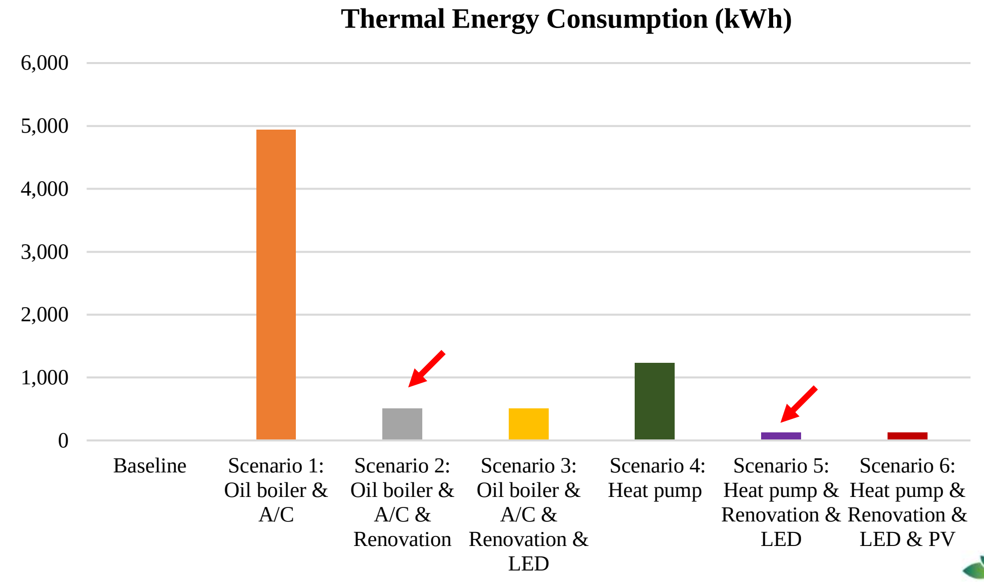
PILOT CASE 3 RESULTS: ENERGY CONSUMPTION

Final Energy, Cooling and appliances, and Thermal energy consumption







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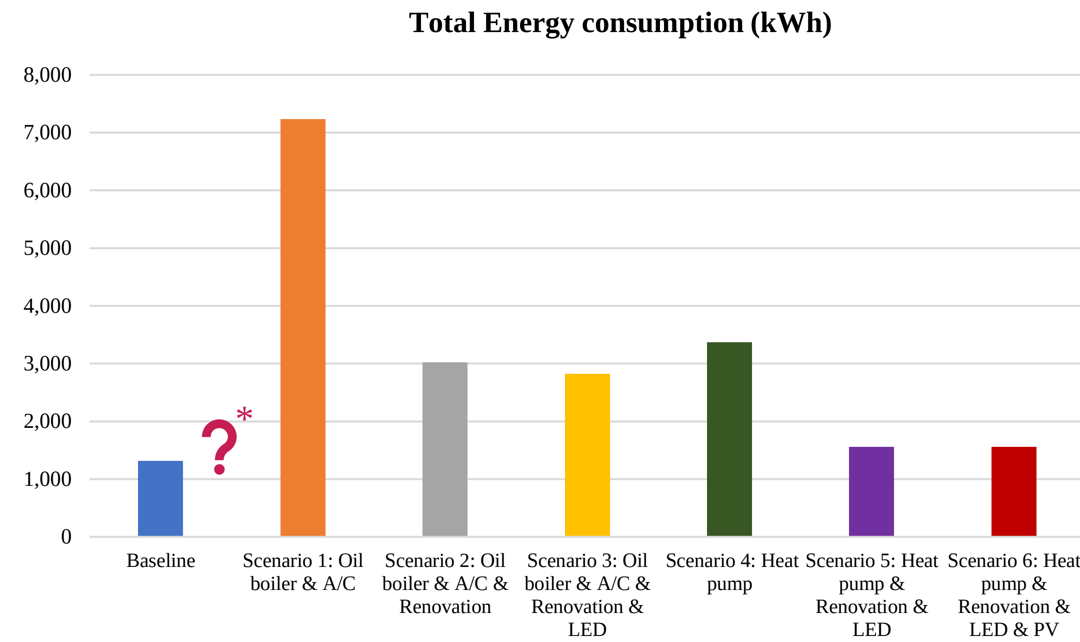
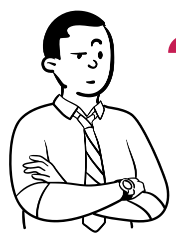
PILOT CASE 3 RESULTS: ENERGY SAVINGS (1/2)

Total annual energy consumption and energy savings

	Total energy consumption (kWh)	Total energy savings (kWh)
Prior Situation: Baseline Scenario	1,311. 1	
Future situation scenario 1: Oil boiler & A/C	7,231.4	
Future situation scenario 2: Oil boiler & A/C & Renovation	3,017.5	4,213.8
Future situation scenario 3: Oil boiler & A/C & Renovation & LED	2,816.8	4,414.5
Future situation scenario 4: Heat Pump	3,369.7	3,861.7
Future situation scenario 5: Heat Pump & Renovation & LED	1,559.2	5,672.1
Future situation scenario 6: Heat Pump & Renovation & LED & PV	1,559.2	7,997.0

Energy savings are calculated compared to Scenario 1!





?* **Increased energy consumption in future situation scenarios?**

No heating system in the baseline scenario!

Pilot case 3 Results: Energy savings (2/2)

Thermal, Cooling & Appliances, and overall annual energy consumption & energy savings

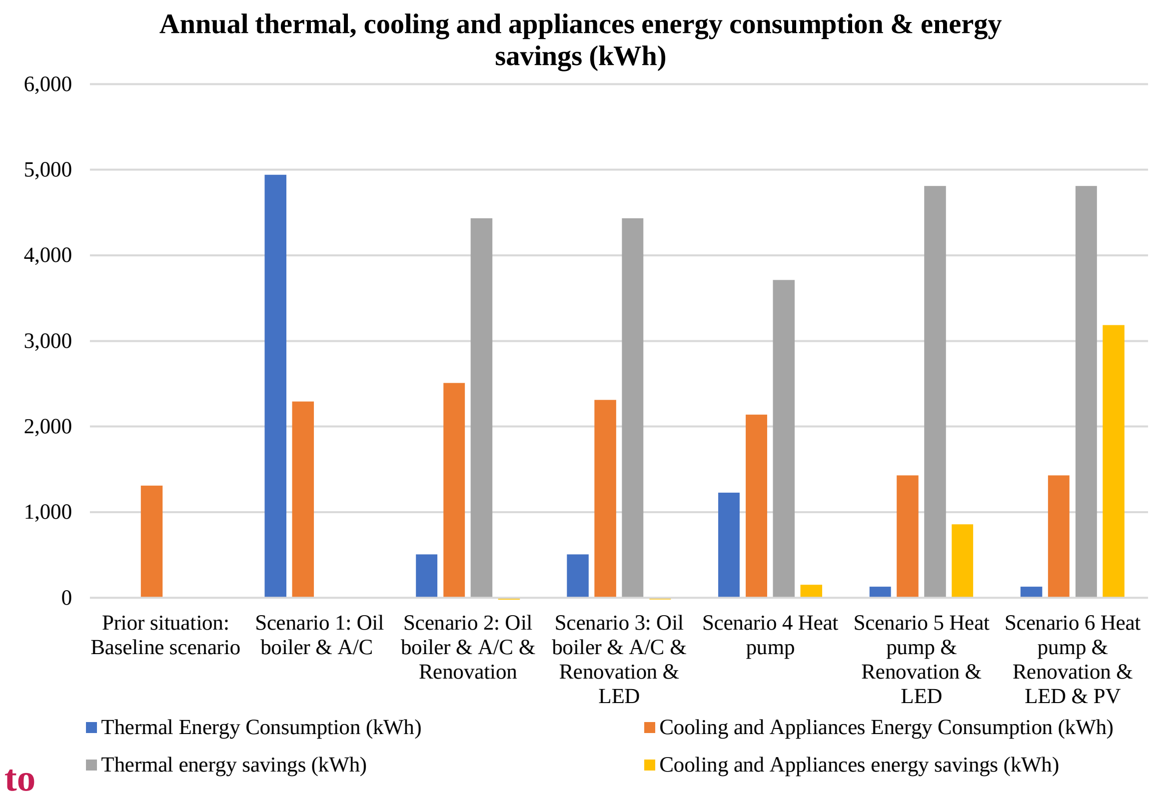
	Energy savings thermal (kWh)	Energy savings cooling and appliances (kWh)
Future situation scenario 2: Oil boiler & A/C & Renovation	4,433.6	-219.7
Future situation scenario 3: Oil boiler & A/C & Renovation & LED	4,433.4	-18.9
Future situation scenario 4: Heat Pump	3,710.9	150.8
Future situation scenario 5: Heat Pump & Renovation & LED	4,812.2	859.9
Future situation scenario 6: Heat Pump & Renovation & LED & PV	4,812.2	3,184.7

Impact of LED lighting (~200 kWh annually)

Effects of building envelope upgrades!

Impact of the PV installation!

Energy savings are calculated compared to Scenario 1!



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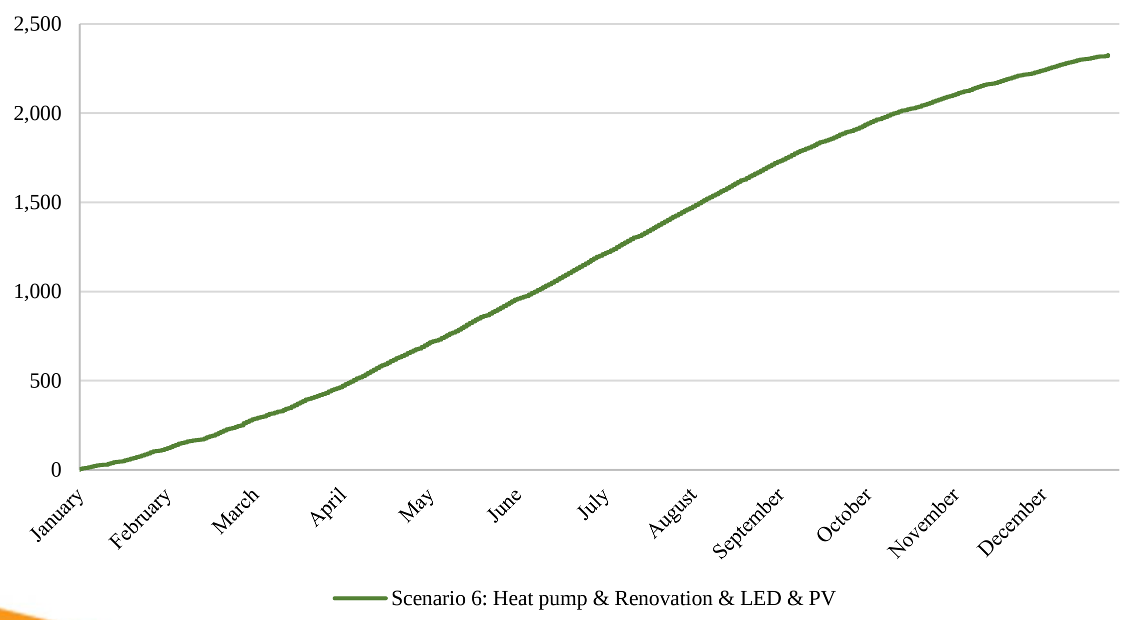
Pilot case 3 Results: PV Generation

Future Situation 6 Scenario → PV Installation

Small-scale residential PV



	Annual electricity consumption (kWh)	Coverage of electricity from the produced solar energy
Scenario 1: Oil boiler & A/C	2,291.0	**101.5%**
Scenario 2: Oil boiler & A/C & Renovation	2,510.7	**92.6%**
Scenario 3: Oil boiler & A/C & Renovation & LED	2,309.9	**100.6%**
Scenario 4: Heat Pump	3,369.6	**69.0%**
Scenario 5: Heat Pump & Renovation & LED	1,559.2	**149.1%**
Scenario 6: Heat Pump & Renovation & LED & PV	1,559.2	**149.1%**

Production of **2,324.8 kWh** per year!

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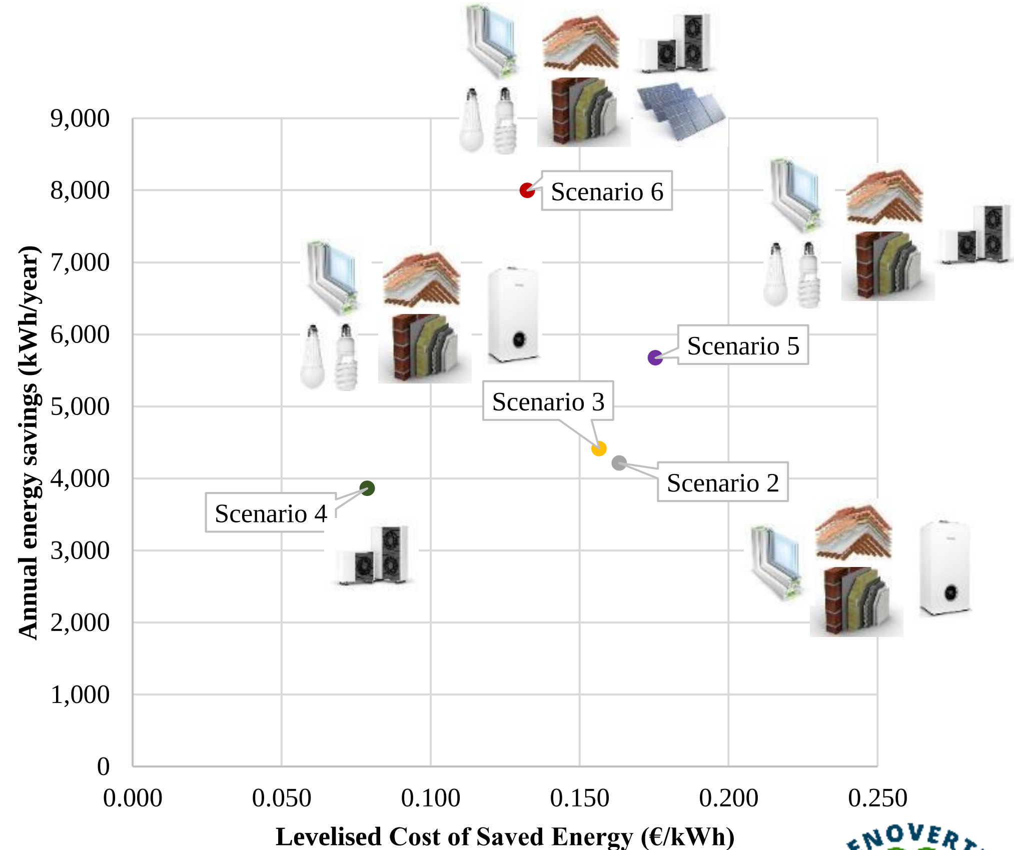
Pilot case 3 Results: Technoeconomic Analysis

	Total energy savings (kWh)	Net Present Value (NPV) (€)	Payback Period (PP) (years)	Levelised Cost of Saved Energy (LCSE) (€/kWh)
Prior Situation: Baseline Scenario	0	0		
Future situation scenario 1: Oil boiler & A/C	0	0		
Future situation scenario 2: Oil boiler & A/C & Renovation	4,213.8	-1,267.02	31.4	0.163
Future situation scenario 3: Oil boiler & A/C & Renovation & LED	4,414.5	-381.37	26.6	0.157
Future situation scenario 4: Heat Pump	3,861.7	1,931.18	15.0	0.079
Future situation scenario 5: Heat Pump & Renovation & LED	5,672.1	-431.93	26.2	0.175
Future situation scenario 6: Heat Pump & Renovation & LED & PV	7,997.0	9,401.98	13.0	0.132

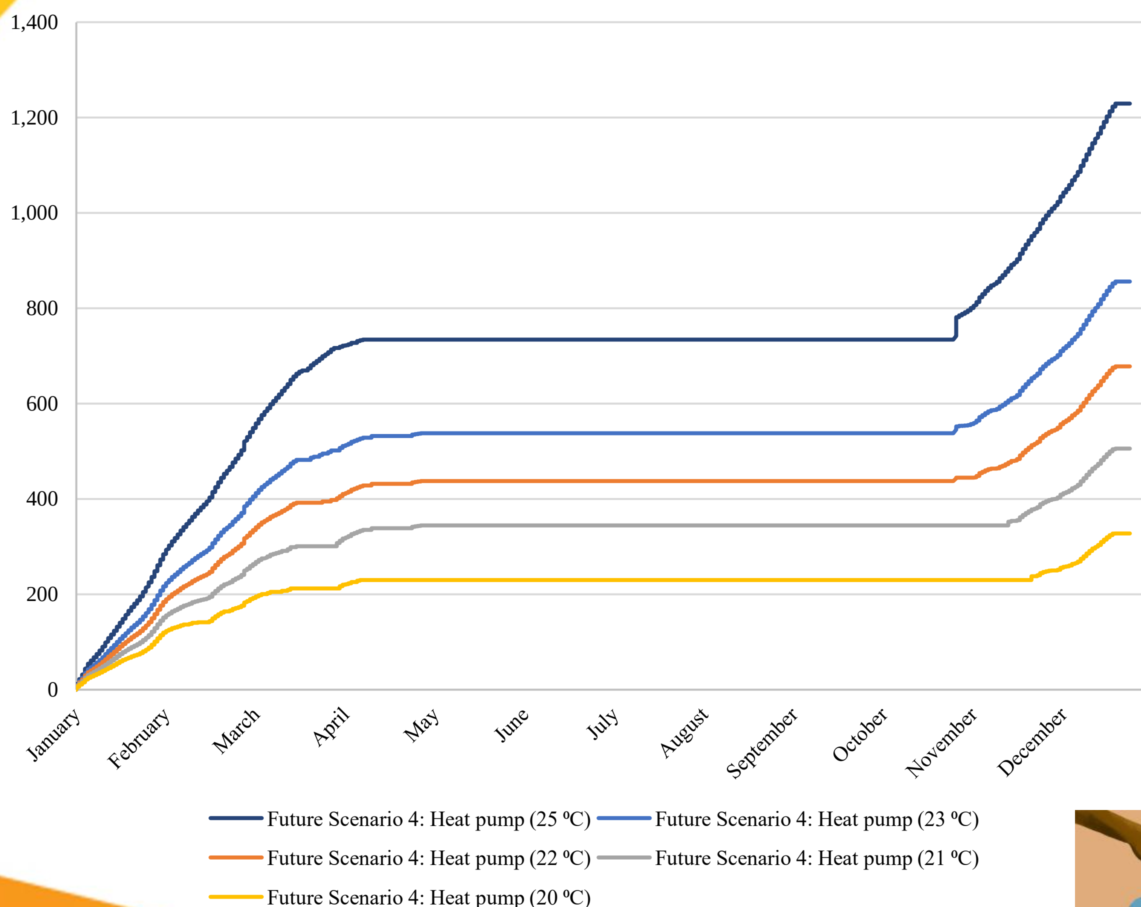
Scenario 6 offers the highest NPV

Scenario 4 is the most cost-efficient in terms of LCSE.



Pilot case 3 Results: Setpoint Adjustments

Cumulative thermal energy consumption (kWh)



	Energy savings thermal (kWh)	Uptake of energy savings	NPV (€)
Future situation scenario 4: Heat Pump (25°C)	3,710.9		1,931.18
Future situation scenario 4: Heat Pump (23°C)	4,084.2	10.1%	3,670.90
Future situation scenario 4: Heat Pump (22°C)	4,262.2	14.9%	3,797.51
Future situation scenario 4: Heat Pump (21°C)	4,434.6	19.5%	4,958.38
Future situation scenario 4: Heat Pump (20°C)	4,612.7	24.3%	5,430.81

Adjusting setpoints from 25 °C to 23 °C during Winter can increase the investment's NPV up to 1,739 €

Cross-Pilot Comparison (1/6)

Pilot case 2

Country: **France**
Region: **Grand Est region**

Type of building/usage: Single Family House

Year of Construction: 1950 to 1980

Building size: Basement level + 2 ground floors

Total floor area: $82m^2$

Heating system: Oil boiler

Pilot case 1

Country: **Spain**
Region: **Gijon region**

Type of building/usage: Multi Family House

Year of Construction: 1958

Building size: Ground floor + 2 floors

Total floor area: $80m^2$ per apartment

Heating system: Electric heaters

Pilot cases 3-4

Country: Portugal

Type of building/usage: Single Family House

Year of Construction: 1988

Building size: 2-storey building (ground + first floor)

Total floor area: 188 m^2

Heating system: Electric heaters

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CROSS-PILOT COMPARISON (2/6)

Pilot case 1 (Gijon region **- Spain)**

Scenario	Measures Implemented
🟠 1	Renovation
2	Renovation & PV
🟡 3	Heat pump
4	Heat pump & Renovation
🔴 5	Heat pump & Renovation & LED & PV

Pilot case 2 (Grand-Est region **- France)**

Scenario	Measures Implemented
🟡 1	Heat pump
🟠 2	Renovation
3	Heat pump & Renovation
4	Heat pump & Renovation & LED
🔴 5	Heat pump & Renovation & LED & PV

Common future scenarios **across** the analysed demo cases:

- 🟠 **Renovation** (e.g., building envelope upgrades)
- 🟡 **Heat Pump**
- 🔴 **Heat pump** & **Renovation** & **LED** & **PV**

! **Let's remember Pilot case 3**

Scenario	Measures Implemented
1	Oil boiler & A/C
🟠 2	Oil boiler & A/C & Renovation
3	Oil boiler & A/C & Renovation & LED lighting
🟡 4	Heat pump
5	Heat Pump & Renovation & LED lighting
🔴 6	Heat Pump & Renovation & LED lighting & PV installation

Pilot case 3 (Torres Vedras **- Portugal)**

Scenario	Measures Implemented
🟠 1	Renovation
2	Renovation & LED lighting
3	Renovation & LED lighting & PV installation
🟡 4	Heat pump
5	Heat Pump & Renovation & LED lighting
🔴 6	Heat Pump & Renovation & LED lighting & PV installation

Pilot case 4 (Portugal)

Cross-Pilot Comparison (3/6)

Common scenario 1: Renovation

	Total energy savings (kWh)	Total energy savings (%)	LCSE (€/kWh)
Pilot case 1	2,022.93	21.2%	0.156
Pilot case 2	13,905.12	43.4%	0.138
Pilot case 3	4,213.84	58.3%	0.163
Pilot case 4	6,743.2	22.2%	0.140

Common scenario 3: Heat pump & Renovation & LED & PV

	Total energy savings (kWh)	Total energy savings (%)	LCSE (€/kWh)
Pilot case 1	4,894.03	51.2%	0.189
Pilot case 2	27,804.08	86.8%	0.092
Pilot case 3	7,996.98	110.6%	0.132
Pilot case 4	29,607.7	97.4%	0.46

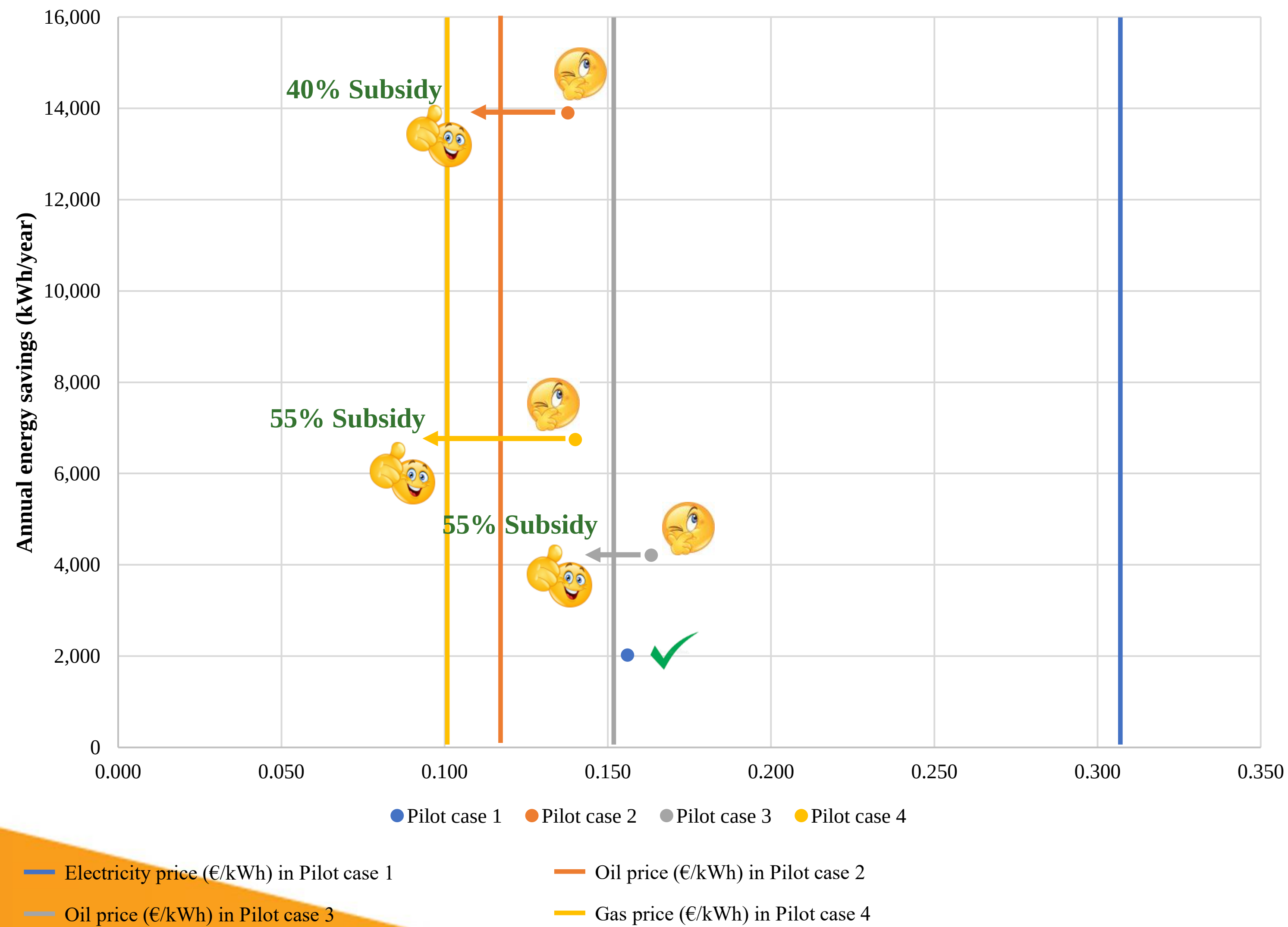
Common scenario 2: Heat Pump

	Total energy savings (kWh)	Total energy savings (%)	LCSE (€/kWh)
Pilot case 1	1,788.0	18.7%	0.322
Pilot case 2	21,372.7	66.7%	0.027
Pilot case 3	3,861.7	53.4%	0.079
Pilot case 4	18,246.4	60.0%	0.017

The **LCSE** for each **future scenario** is compared with the **energy price** of the **baseline scenario's energy carrier**.

CROSS-PILOT COMPARISON (4/6)

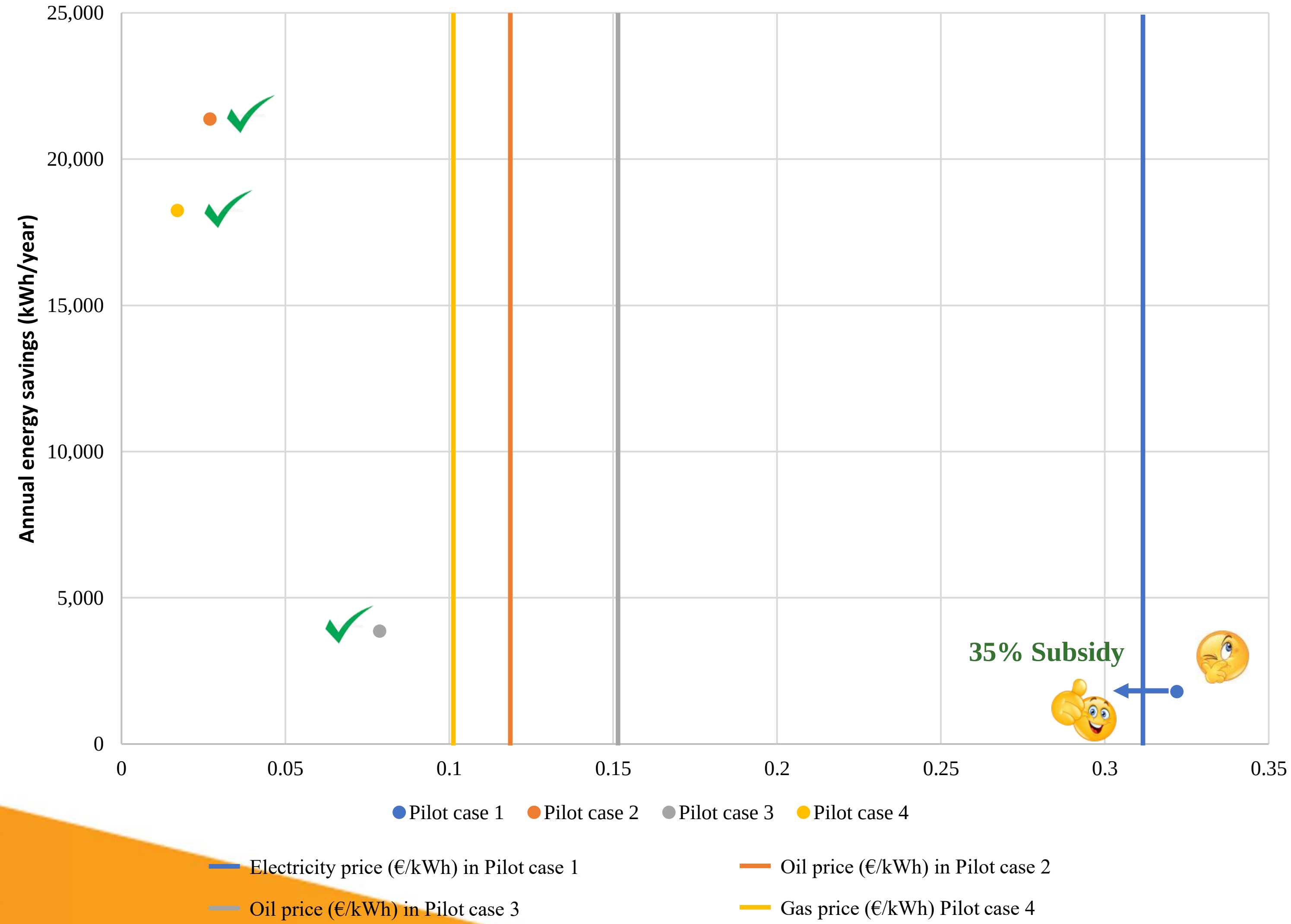
Common scenario 1: Renovation



Necessary subsidy rates for renovation!

Cross-Pilot Comparison (5/6)

Common scenario 2:
Heat Pump



Electrification of heating systems

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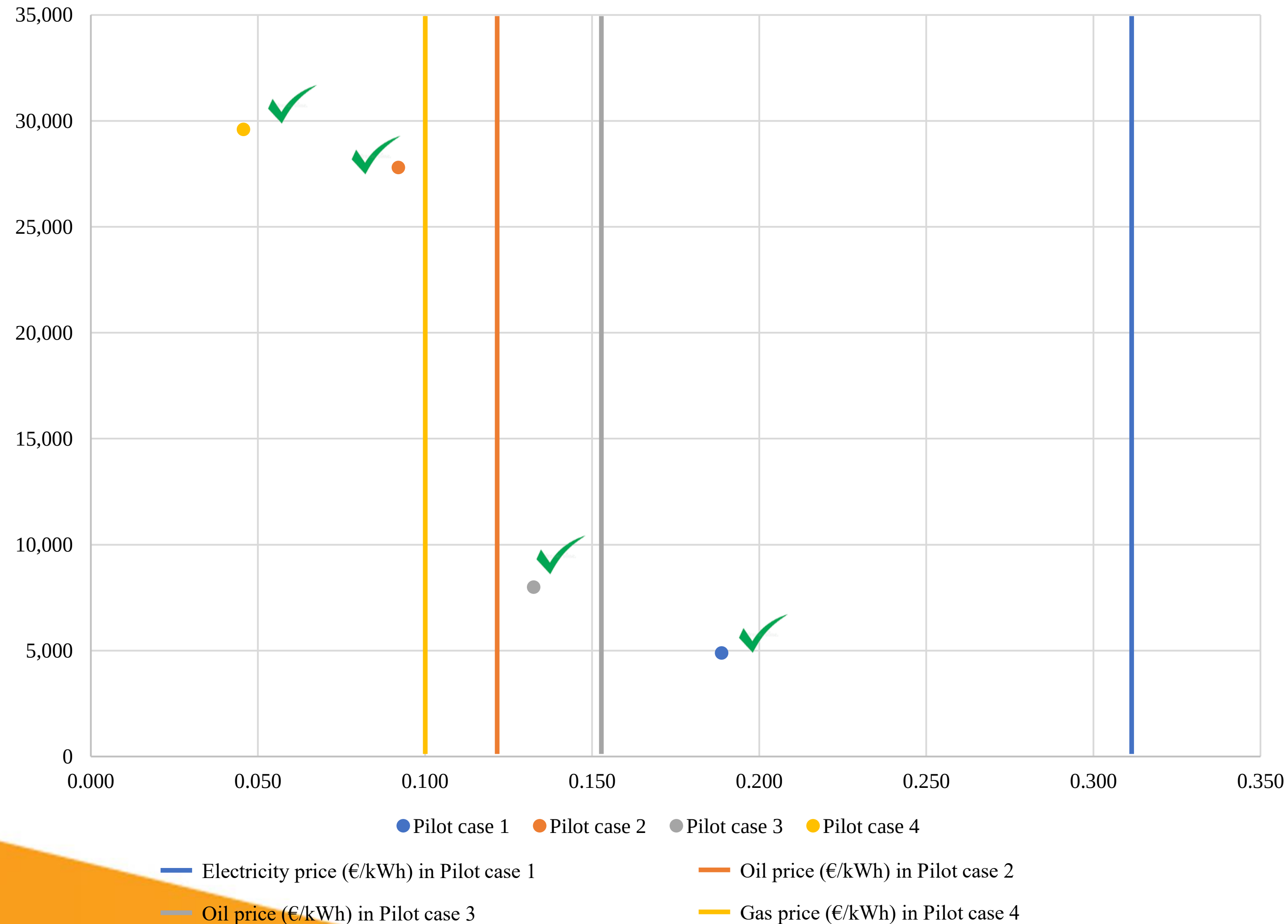
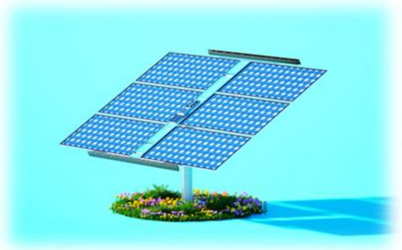
Cross-Pilot Comparison (6/6)

Common scenario 3:
Heat pump & Renovation & LED & PV



Benefits of coupling energy efficiency actions with **renewable generation** despite the **higher upfront costs**



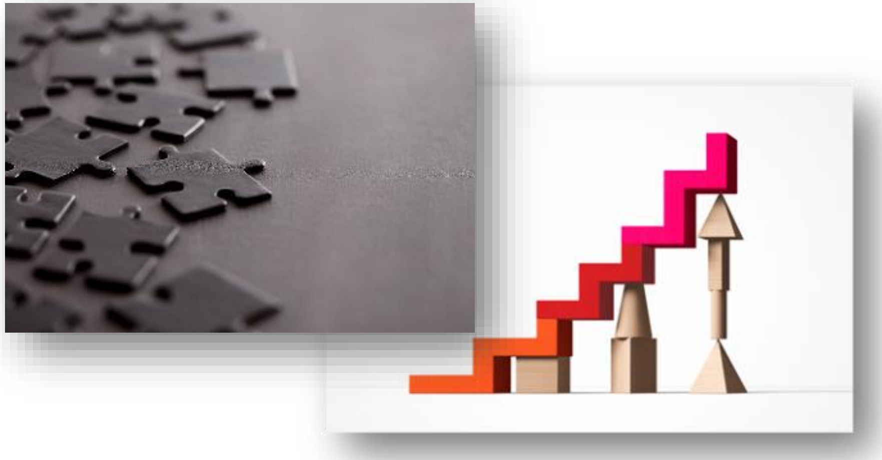
Conclusions and next steps

Useful findings and remarks

- ✓ **Prioritise** the **substitution** of fossil fuel boilers with **heat pumps** the most beneficial in terms of **energy savings** and **economic viability**.
- ✓ **Differentiate** the renovation packages according to the **typology**
  - ❖ **single family houses** → **building envelope upgrades**
  - ❖ **multi family houses** → installation of **heat pumps**.
- ✓ **Coupling energy efficiency** actions with **renewable generation** offers **significant** benefits for households, despite the **higher upfront costs**.
- ✓ **Quantification of behavioural changes** (e.g., adjusting **heating** and **cooling setpoints**) → changes in the investment's **profitability (NPV)** and technoeconomic performance

Next research steps:

- ❑ Extend the analysis to more countries/ regions across the EU.
- ❑ Focus on more real-life pilots.
- ❑ Expedite **renovation packages** for upscale across EU.



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