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ThermoPro: Advanced Insulation Analysis & Energy Optimization Tool

"Empowering smarter energy decisions with a tool that transforms insulation challenges into cost-saving, sustainable solutions for buildings, vehicles, and extreme environments."

PROBLEM STATEMENT:

Buildings lose significant energy due to poorly insulated walls, leading to higher energy bills, increased carbon emissions, and environmental challenges. Heat escapes through various ways: gaps in walls (convection), direct transfer through materials (conduction), or radiation from surfaces. However, developers, engineers, and facility managers often lack a user-friendly tool to assess how different insulation materials and setups perform under real-world conditions, such as varying weather, wind, or humidity.

Solution Goal:

This tool aims to simplify material selection and improve energy efficiency by:

- *Helping users compare materials and identify the most energy-efficient and cost-effective insulation materials across different temperature ranges.*
- *Providing a clear view of how small adjustments in thickness and conductivity significantly influence insulation performance.*
- *Presenting all results in a single, streamlined view for quick and informed decision-making.*

Features and Benefits:

With color-coded insights, downloadable results, and easy-to-read tables, this tool offers practical support for applications in construction, HVAC design, and energy audits.

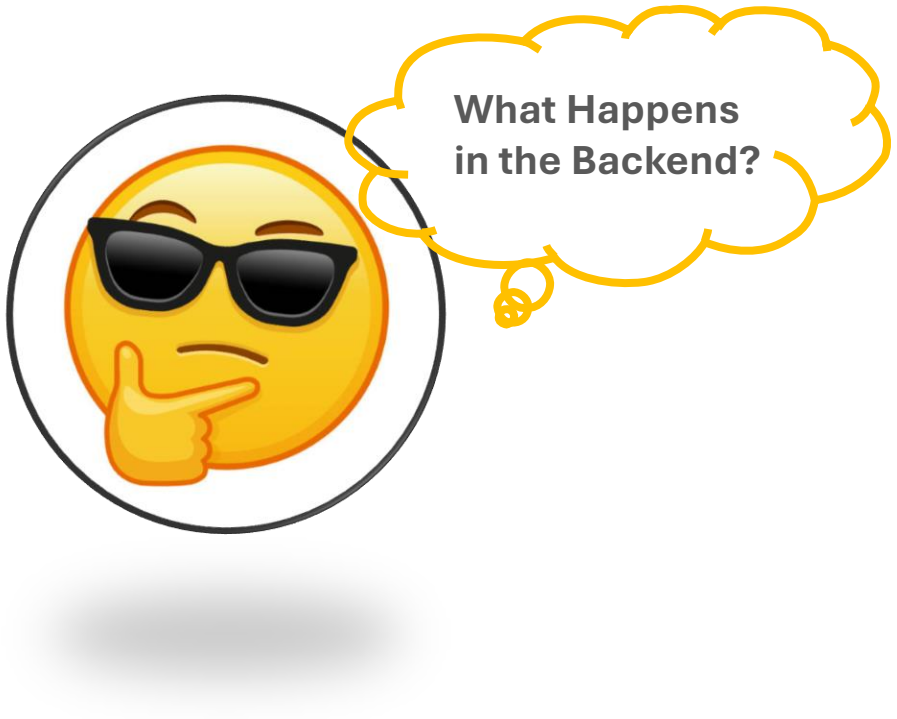
Beyond Buildings:

This concept extends beyond buildings, offering solutions for factories, vehicles, airplanes, and even extreme climate-resistant structures. By combining heat transfer science with an intuitive interface, it translates complex challenges into practical and user-friendly solutions that save energy and money.

➢ **App**: https://thermopro-6xt7ciztbdvpwz5u75m736.streamlit.app/
➢ **GitHub:** https://github.com/JAYAPRAKASHCHANDRAN/thermoPro

APPROACH:

- **Dynamic Material Configuration**: Users can input and compare multiple wall material configurations by specifying properties like thickness and conductivity.
- **Thermal Analysis**: Calculates Effective (total) thermal resistance (R-value), heat flux per unit area, and total heat flux based on temperature differences and wall area.
- **Energy Cost Estimation**: Provides annual energy cost predictions by considering energy rates and operating hours.
- **Interactive Visualization**: Generates intuitive graphs to compare heat flux across materials, with dynamic legends and customizable axis labels.
- **Detailed Results**: Displays heat flux, thermal resistance, and energy cost in an interactive table, highlighting the most and least effective materials.
- **Insights and Export Options**: Summarizes the best effective and least effective-performing materials and allows users to export results as a CSV file for reporting.



The system calculates:

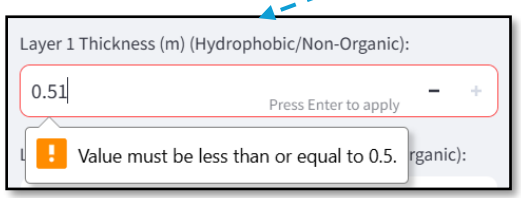
- **Heat Flux (W/m^2)**: Heat transfer per unit area.
- **Total Heat Flux (W)**: Total heat transfer across the entire area.
- **Wall Area (m^2):** The total wall area is calculated to determine the heat transfer across the material.
- **Thermal Resistance ($K \cdot m^2/W$)**: The material's resistance to heat flow.
- **Annual Energy Cost ($)**: Cost of operating under the given conditions.
- **Comparison:** The temperatures are compared (e.g., 250–300K) with either of the fixed temperatures and generate results in a single view.

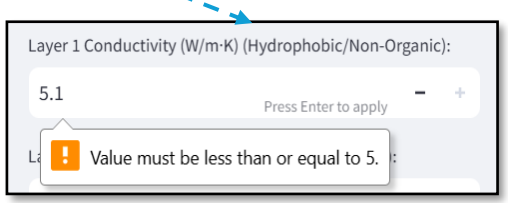
HOW TO USE THE WORKFLOW - 1:

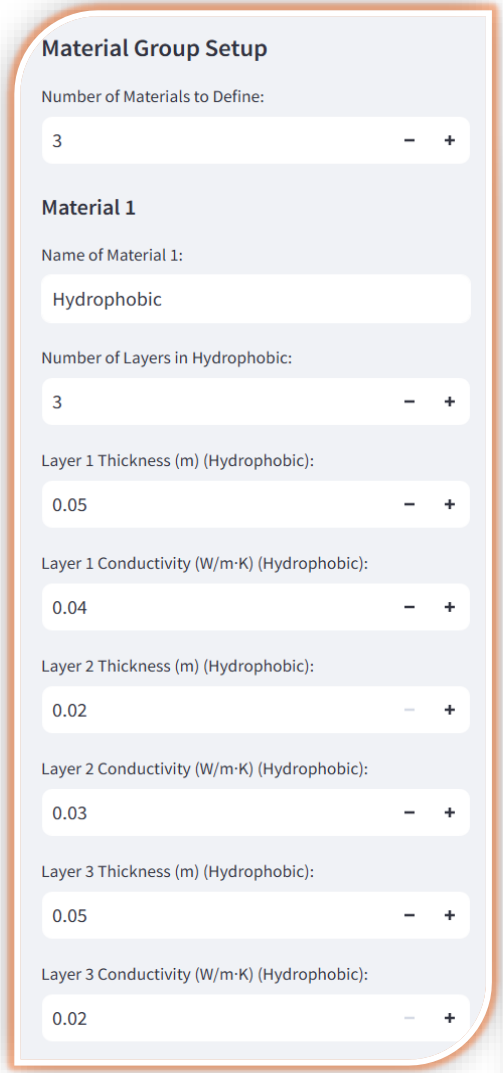
Input Materials and Properties

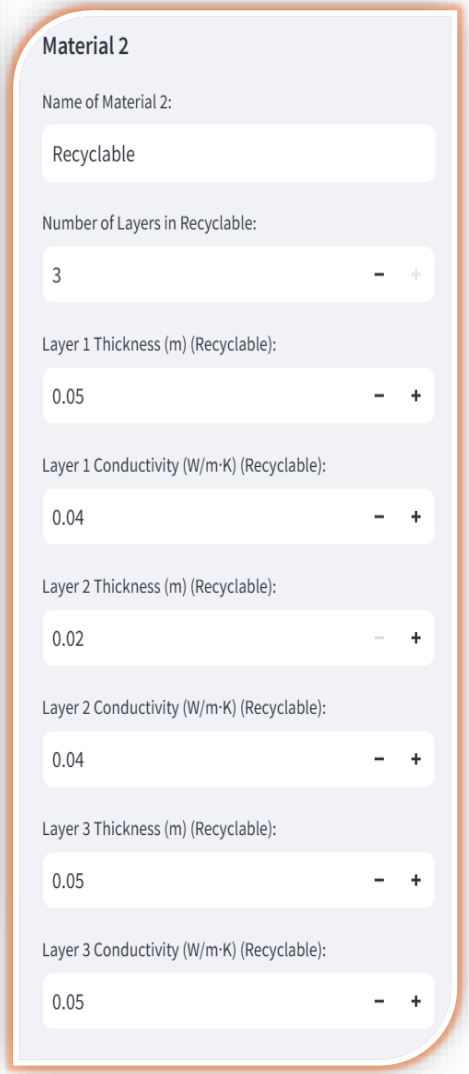
- **Sidebar Configuration**:
  - User defines “n” materials (0 to n) with custom names.
  - Add multiple layers for each material, specifying:
    - **Thickness (m)**: The thickness of each layer.
    - **Thermal Conductivity (W/m·K)**: A measure of how well the material conducts heat.
  - **Example:**
    - Material: “Material A”
    - Layers:
      - Layer 1: 0.05 m thickness, 0.04 W/m·K conductivity.
      - Layer 2: 0.02 m thickness, 0.03 W/m·K conductivity.

To ensure accurate thermal analysis the input values are kept within realistic physical limits. **For example,** if the thickness exceeds ***0.5 meters*** or thermal conductivity goes beyond ***5 W/m·K***, the form displays clear error messages like "Value must be less than or equal to ***0.5,"*** *guiding user to enter valid inputs*.





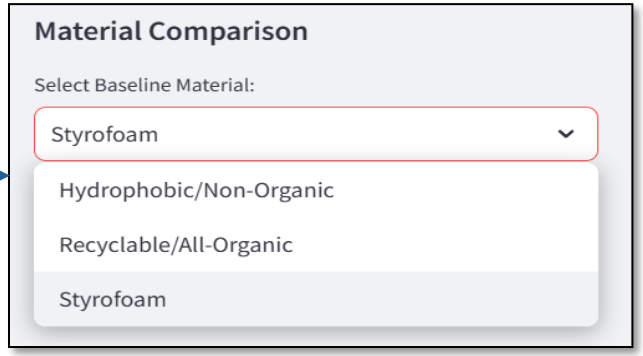




HOW TO USE THE WORKFLOW - 2:

Select Baseline Material:

- **Purpose**: The baseline material serves as the reference point for comparison with other materials.
- **Dropdown**: Users select a material (e.g., "Styrofoam") from the available list of defined materials.
- **Functionality**: The baseline material will be used to calculate and compare thermal properties like heat flux, thermal resistance, and energy cost with other materials.

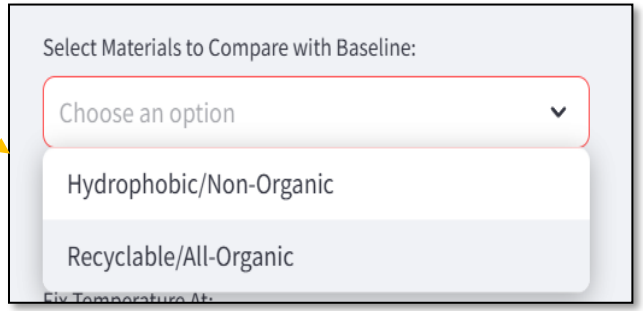


Select Materials to Compare with the Baseline:

- **Purpose**: Allows the user to select one or more materials to compare against the baseline material.

- **Multiselect Field**:
  1. In the example, "Hydrophobic/Non..." and "Recyclable/All-O..." are selected as comparison materials.
  2. The materials in red indicate they've been chosen for the analysis.
  3. The **"X"** allows the user to deselect a material.

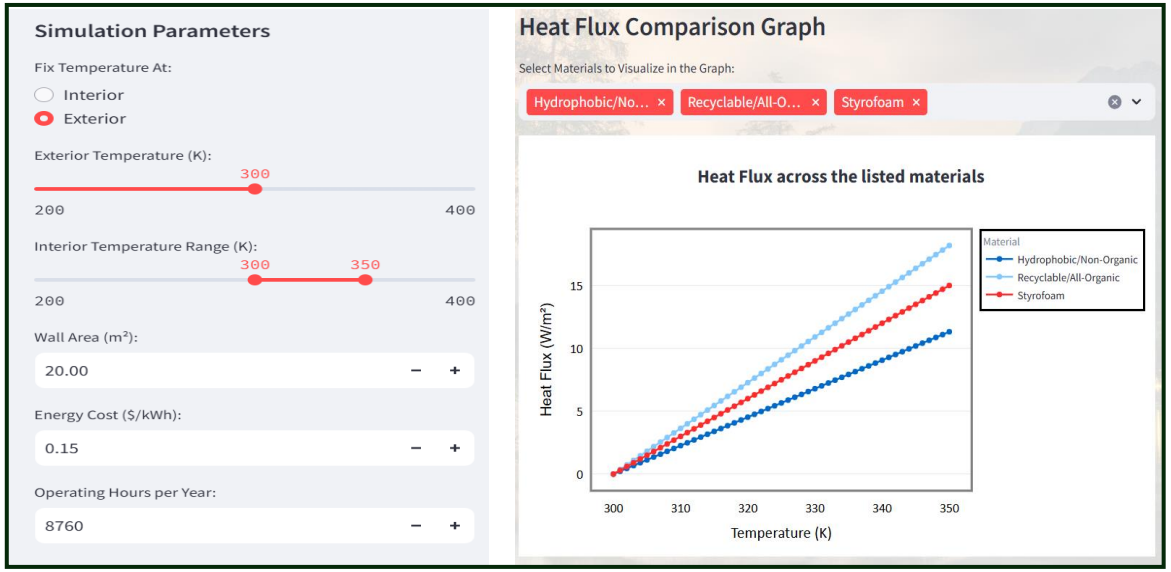
- **Functionality**: These selected materials will be compared with the baseline for metrics such as:
  1. Heat flux per unit area.
  2. Total energy cost.
  3. Thermal resistance effectiveness.

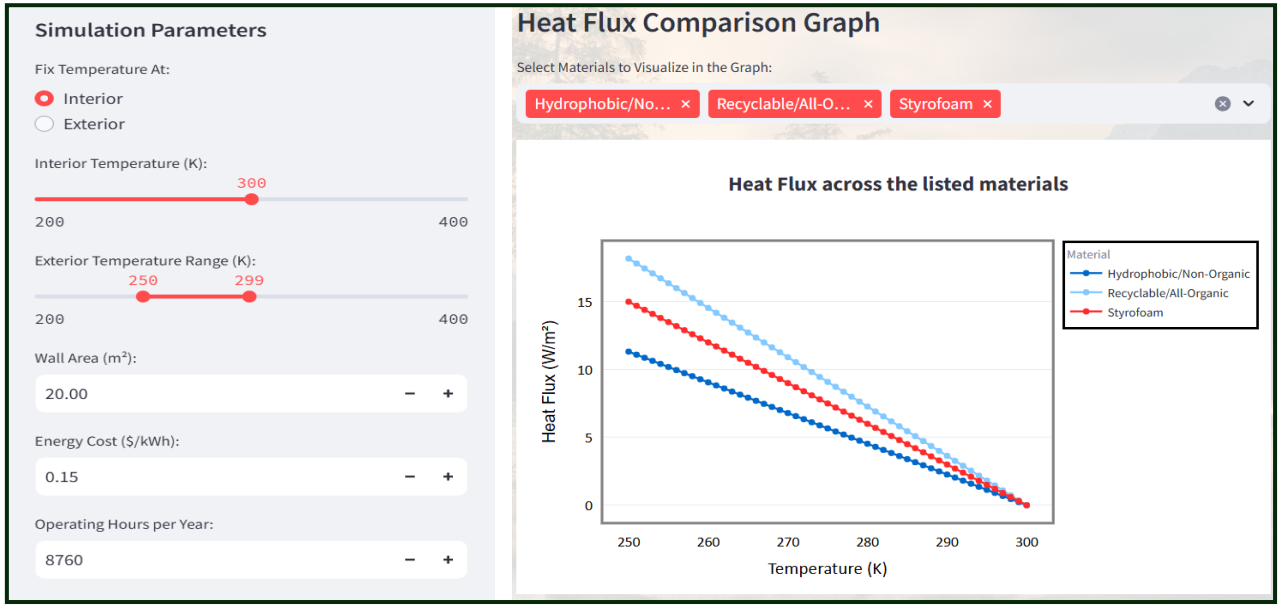


HOW TO USE THE WORKFLOW - 3:

- **User Defines:**
  - **Fixed Temperature**: Either *"Interior"* or *"Exterior."*
  - **Temperature Range**: A range of varying temperatures to simulate real-world conditions.
  - **Wall Area**: The area (in square meters) of the wall or structure being analyzed.
  - **Energy Cost ($/kWh)**: The cost of electricity per kilowatt-hour.
  - **Operating Hours**: Annual usage in hours.

Exterior Temp as "Fixed"





Interior Temp as "Fixed"

HOW TO USE THE WORKFLOW – 4:

The **Detailed Results Table** helps users compare materials across a temperature range (e.g., 250K to 298K) to identify the most energy-efficient and cost-effective options. It highlights key metrics like:

The table pops with *"If the interior or exterior temperature is fixed, these values represent the range"*.

Detailed Results Table

If interior temperature is 300K, the results are for the range between 250K and 298K.

	Material	Temperature (K	Heat Flux (W/m²)	Total Heat Flux (W)	Effective Thermal Resistance (K·m²/W)	Annual Energy Cost ($)	Effectiveness
0	Hydrophob	250	11.320755	226.415094	4.416667	297.509434	Most Effective
49	Recyclable/	250	18.181818	363.636364	2.750000	477.818182	Least Effective
98	Styrofoam	250	15.000000	300.000000	3.333333	394.200000	Comparison
1	Hydrophob	251	11.094340	221.886792	4.416667	291.559245	Most Effective
50	Recyclable/	251	17.818182	356.363636	2.750000	468.261818	Least Effective
99	Styrofoam	251	14.700000	294.000000	3.333333	386.316000	Comparison
2	Hydrophob	252	10.867925	217.358491	4.416667	285.609057	Most Effective
51	Recyclable/	252	17.454545	349.090909	2.750000	458.705455	Least Effective
100	Styrofoam	252	14.400000	288.000000	3.333333	378.432000	Comparison
3	Hydrophob	253	10.641509	212.830189	4.416667	279.658868	Most Effective
52	Recyclable/	253	17.090909	341.818182	2.750000	449.149091	Least Effective
101	Styrofoam	253	14.100000	282.000000	3.333333	370.548000	Comparison

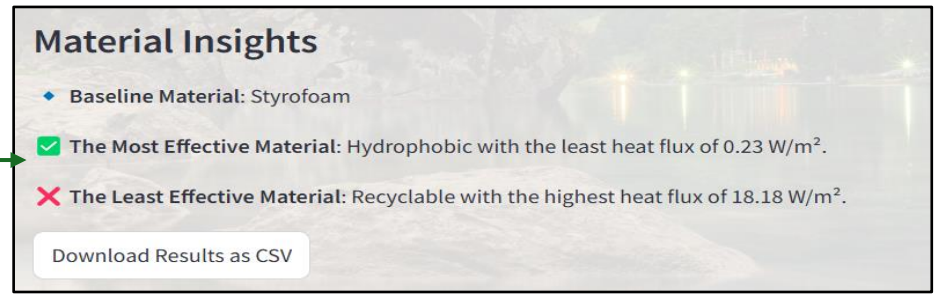
Color coding

Green: *Represents the most effective material in terms of low heat flux.*
Red: *Highlights the least effective material with the highest heat flux.*
Blue: *Marks the baseline material (used as the reference point for comparison).*

Material Insights

The user gets a pop-up that *says, " Across these temperatures, this material offers the most effective and least effective."*

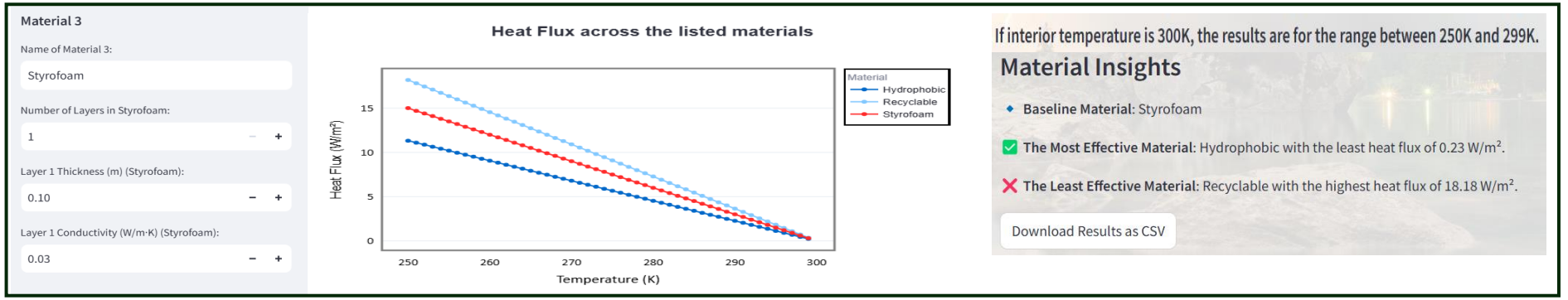
1. **Baseline Material**: Styrofoam, used as the comparison.
2. **Most Effective**: Hydrophobic/Non-Organic (heat flux: 0.23 W/m^2), offering excellent insulation.
3. **Least Effective**: Recyclable/All-Organic (heat flux: 18.18 W/m^2), less energy-efficient.
4. **Download:** Users can download the results as a CSV for further analysis or documentation.

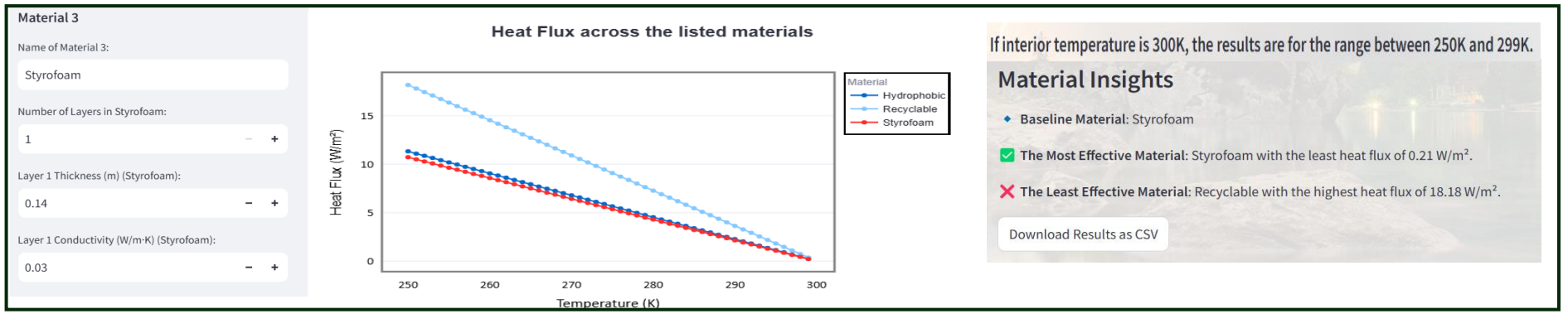


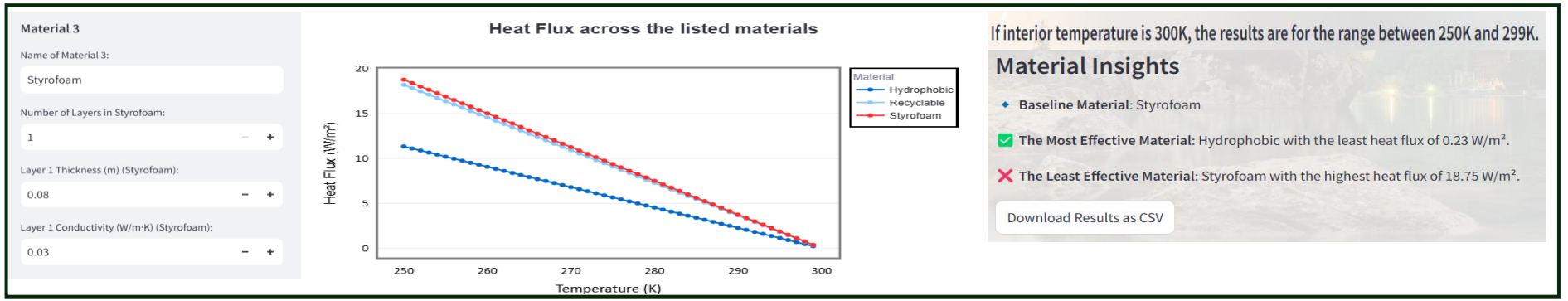
*** All data and material are used for reference only; actual value and name may differ.**

HOW TO USE THE WORKFLOW – 5:

How small changes can affect the insulation, let's see the magic of the tool:



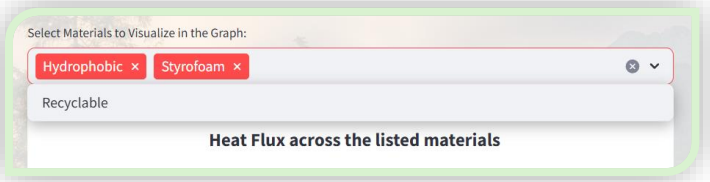




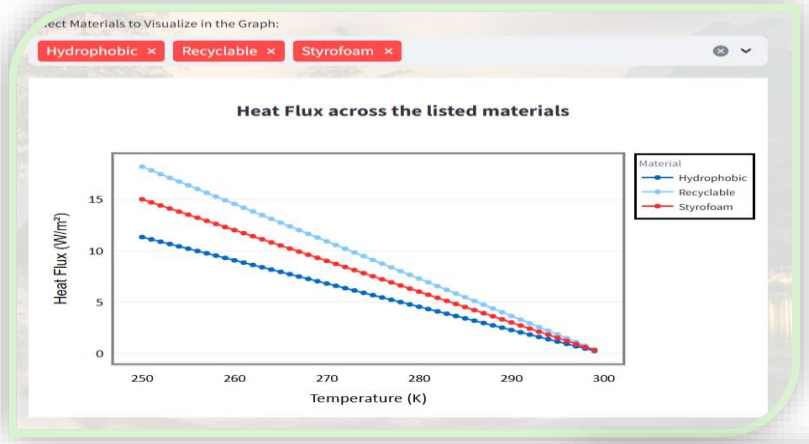
- With a **0.10 thickness**, Styrofoam is neither the most nor the least effective material.
- When the thickness is increased to **0.14**, Styrofoam becomes the **most effective material**, showing excellent performance across temperature ranges.
- Reducing the thickness to **0.08** makes Styrofoam the **least effective material**, with poor performance highlighted in the graph.
- The graphs clearly illustrate how changes in thickness affect heat flux and insulation performance.

😎 This tool helps users easily predict material performance by visualizing how thickness/conductivity impacts efficiency across different temperature ranges. 😎

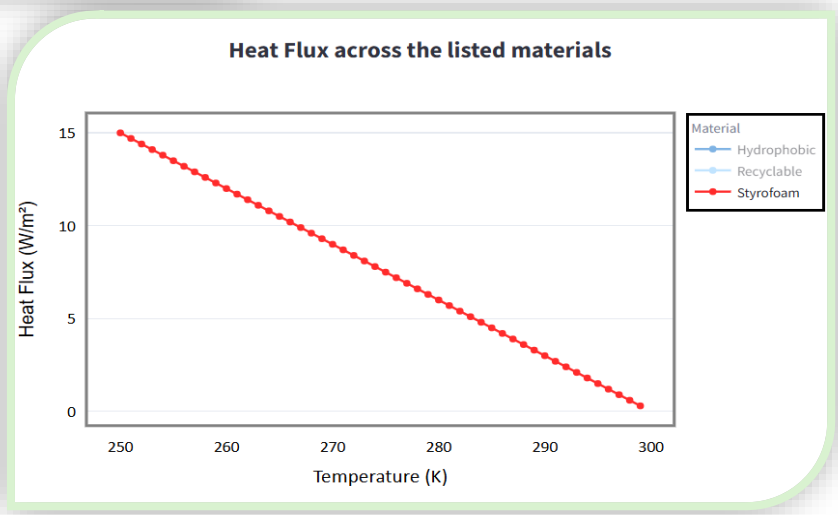
KEY FEATURES OF THE UI - 1:



User can select features from the dropdown once materials are added to the "*materials comparison*" section for analysis.

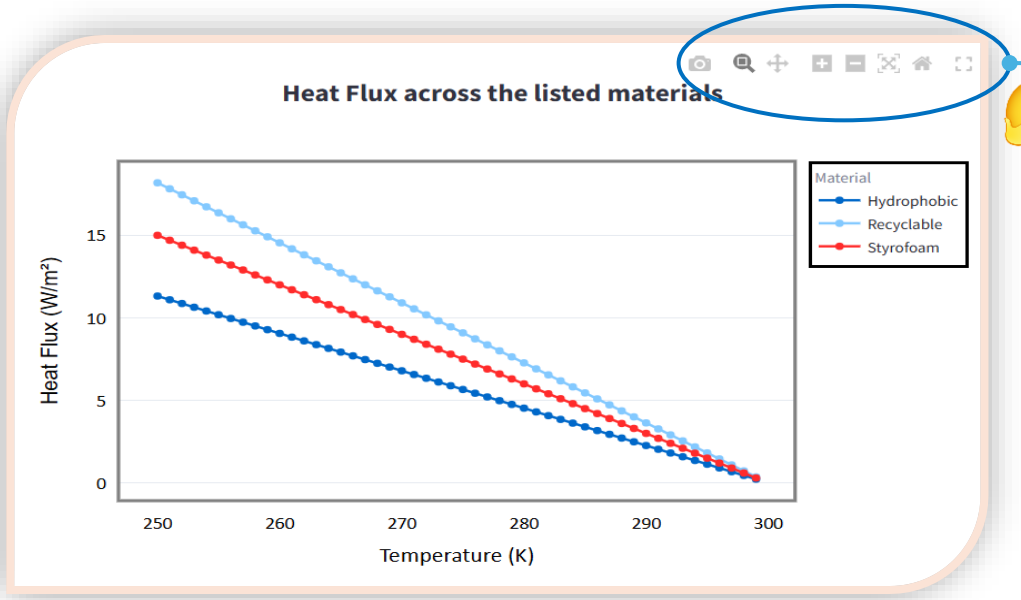


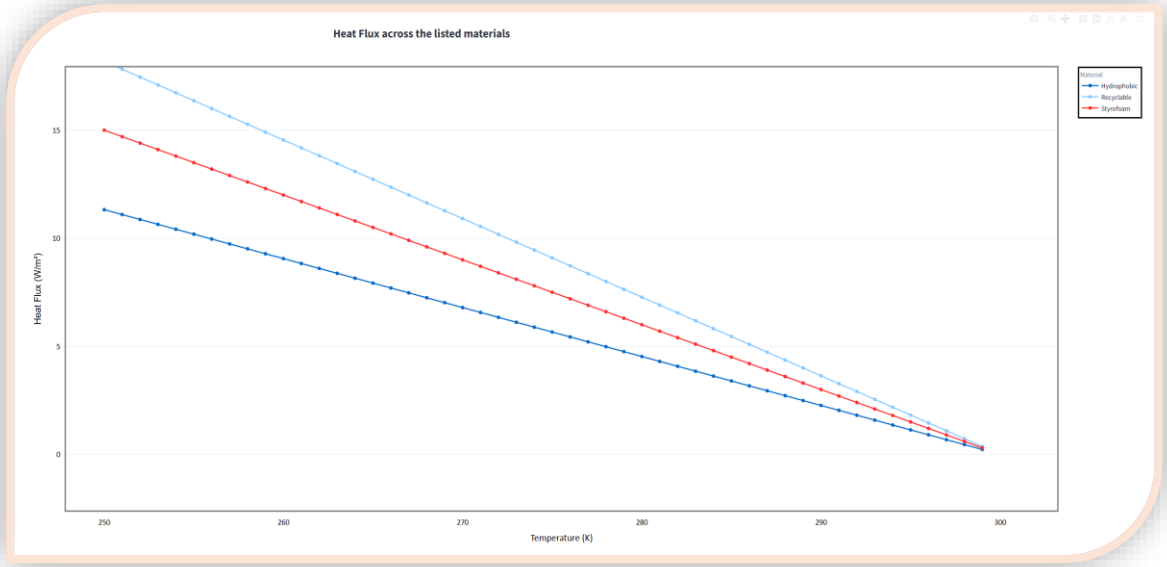
Also, Materials can be enabled or disabled directly on the left side of the graph for customized viewing.

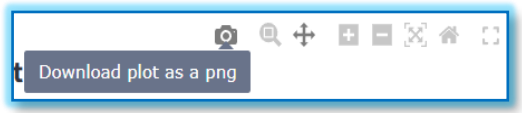


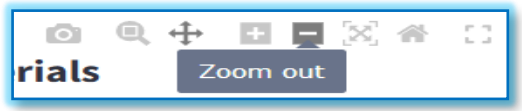
Hidden materials become invisible, improving data clarity and focus on specific material.

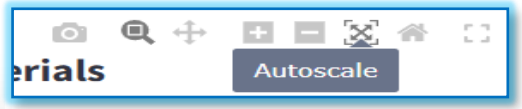
KEY FEATURES OF THE UI - 2:







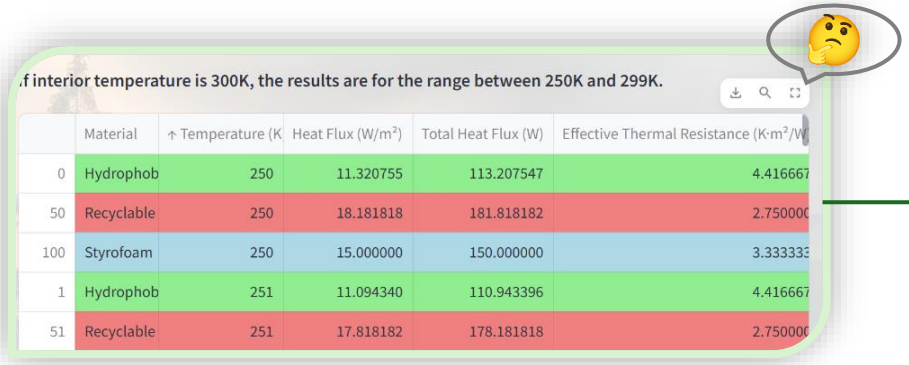




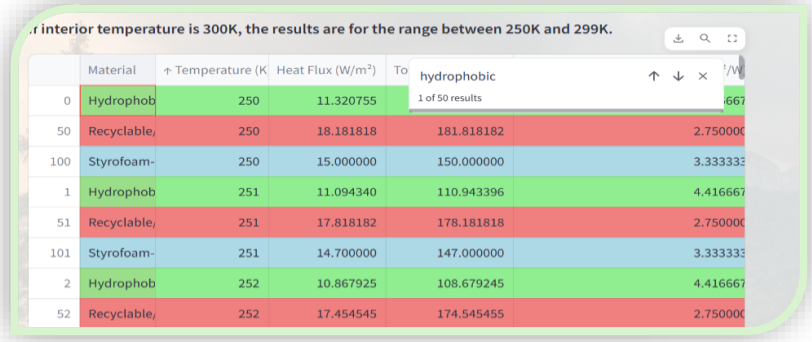
- **Download Plot as a PNG:** Easily save the graph as an image for reports, presentations, or sharing with others.
- **Zoom:** Focus on specific areas of the graph by zooming in for a closer look at data details.
- **Pan:** Move around the graph to explore different sections without losing your zoomed-in view.
- **Zoom In/Out:** Quickly expand the view to see more data or return to a broader perspective.
- **Autoscale:** Restore the axes to fit the data perfectly, ensuring everything is visible.

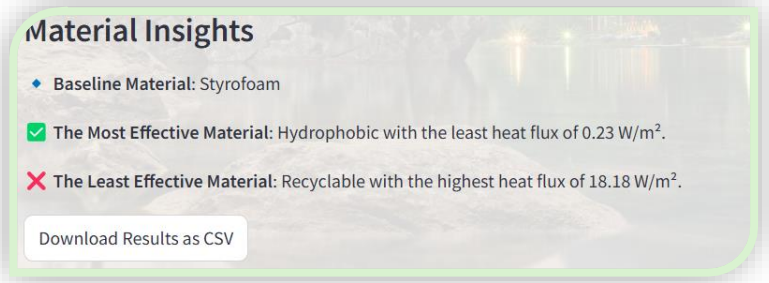
Fullscreen: Expand the graph to fill the entire screen for a clearer and more immersive view.

KEY FEATURES OF THE UI - 3:

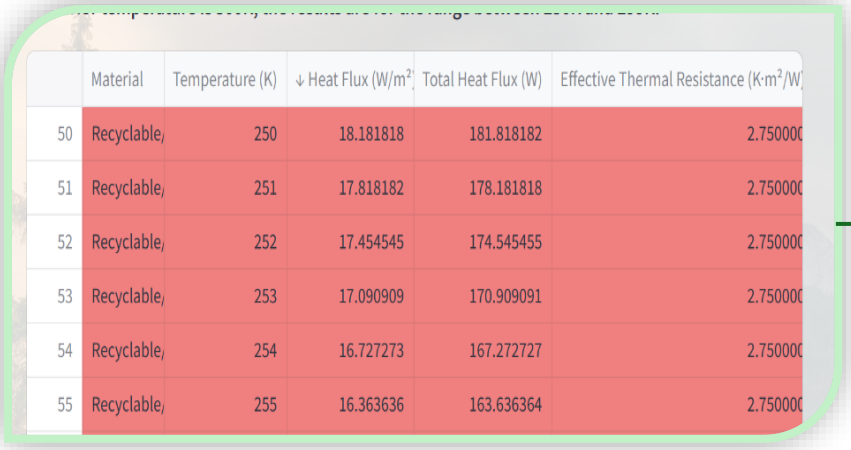


If a user wants to search for specific numbers, materials, or any data, simply click on the search bar to get the results.

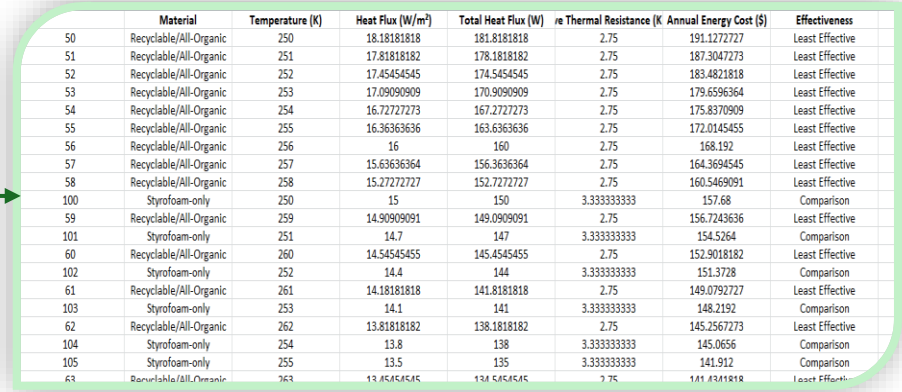




Full-screen mode allows users to view more data in a single, expanded view. Also, they can download the data in CSV.



- If a user wants specific numbers from any column in the table, they can double-click the column heading to sort the data in ascending or descending order based on the column title.
- *For example*, double-clicking the **"Heat Flux"** column displays an arrow near the title, indicating the column is sorted from least to greatest or vice versa. Users can also download the data as an Excel file, eliminating the need for manual sorting.



- The **ThermoPro** is designed to make material comparison and decision-making simple and intuitive. With features like sorting, searching, and downloading results, it ensures users can quickly access and analyze the data they need.
- The visually appealing graphs and detailed tables make understanding complex thermal properties straightforward, even for non-technical users.
- By focusing on ease of use and interactivity, this tool bridges the gap between technical analysis and practical decision-making, providing a seamless experience for everyone involved.

Open Source Model with EmbedAnything Framework

```
Time taken to load the model: 0.91 seconds
Time taken to embed images: 0.35 seconds
Embedding dimensions for image4.png: 512
Embedding dimensions for image2.png: 512
Embedding dimensions for image5.png: 512
Embedding dimensions for image3.png: 512
Embedding dimensions for image1.png: 512
Time taken to embed query: 0.02 seconds
Most similar image: image2.png
Similarity score: 0.30
```

Most Similar Image: image2.png
Similarity: 0.30

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Total time taken: 1.66 seconds
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Closed Source Multi-modal Embedding API

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Embedding dimensions for image4.png: 1024
Embedding dimensions for image2.png: 1024
Embedding dimensions for image5.png: 1024
Embedding dimensions for image3.png: 1024
Embedding dimensions for image1.png: 1024
Time taken to embed images: 2.06 seconds
Time taken to embed query: 0.10 seconds
Most similar image: image2.png
Similarity score: 0.6306813208749484
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Most Similar Image: image2.png
Similarity: 0.63

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Total time taken: 2.43 seconds
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