POSITION PAPER

Thermophotovoltaic (TPV) Conversion for Nuclear Reactor Applications

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Abstract

Thermophotovoltaic (TPV) conversion technology leverages thermal radiation emitted by high-temperature sources to generate electricity using photovoltaic (PV) cells. Its compact design, lack of moving parts, and potential for high efficiency make TPV systems an attractive alternative for integrating with Small Modular Reactors (SMRs) and micro-nuclear reactors operating at temperatures above ~800°C. This paper explores the detailed physics, processes, material properties, computational modeling, system designs, challenges, and economic analysis of TPV technology, with a focus on its application in nuclear energy systems.

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1. Introduction

TPV conversion uses high-temperature sources to emit thermal radiation, which is subsequently converted into electricity via specially designed PV cells. This approach has gained attention for its potential in SMRs and microreactors, which prioritize compactness, efficiency, and safety.

Key Advantages of TPV:

1. High-temperature operation with efficient thermal-to-electric conversion.
2. Modular and compact systems with minimal mechanical complexity.
3. Potential for integration with high-temperature reactors and other industrial processes.

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2. Physics of TPV in Nuclear Reactors

2.1. Thermal Radiation

Thermal radiation from a high-temperature reactor core is governed by:

- Planck's Law: Describes the spectral intensity of emitted radiation.
- Stefan-Boltzmann Law: Relates emitted power to temperature (P=σT4P = \sigma T^4P=σT4).

For reactor cores operating at 800–1200°C, thermal radiation peaks in the NIR spectrum, making materials such as GaSb PV cells optimal.

2.2. Spectral Control

Effective TPV systems rely on controlling the spectrum of thermal radiation:

- Selective Emitters: Emit wavelengths matching the PV cell's bandgap.
- Filters and Reflectors: Recycle unused radiation back to the emitter.

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3. Processes in TPV for Nuclear Reactors

3.1. Heat Source

The reactor core provides a stable, high-temperature heat source:

- Operating Temperatures: 800–1200°C for microreactors.
- Direct or Indirect Coupling: Heat transfer using conduction or heat pipes.

3.2. Thermal Emitters

Emitters convert reactor heat into electromagnetic radiation:

- Materials: Tungsten or rare earth oxides for selective emissivity.
- Design: Optimized for durability and spectral control.

3.3. Spectral Control Layers

Filters and reflectors enhance system efficiency:

- Spectral Filters: Transmit radiation in the PV-absorbable range while reflecting unused wavelengths.
- Recycling Systems: Redirect reflected radiation back to the emitter for reuse.

3.4. Photovoltaic Cells

PV cells convert thermal radiation into electricity:

- Narrow-Bandgap Semiconductors: GaSb cells for high efficiency in the NIR.
- Multi-Junction Cells: Layered designs for broader spectral absorption.

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4. Detailed Material Properties

4.1. Thermal Emitters

- Tungsten (W)
  - Properties:
    - Melting Point: ~3422°C.
    - Thermal Conductivity: 173 W/m·K.
    - Emissivity: Tailorable for NIR spectrum using coatings.
  - Strengths: Stability at high temperatures and radiation resistance.
  - Weaknesses: Oxidation risk at lower temperatures.
- Rare Earth Oxides (Lanthanum Hexaboride, Ytterbium Oxide)
  - Properties:
    - High emissivity in NIR.
    - Thermal Stability: >2000°C.
  - Strengths: Long lifespan under extreme conditions.
  - Weaknesses: High material and fabrication costs.

4.2. Spectral Control Layers

- Spectral Filters
  - Materials: Dielectric coatings, alternating SiO_2/TiO_2 layers.
  - Properties:
    - Reflectivity: >95% outside PV absorption range.
    - Thermal Resistance: Up to 800°C.
  - Strengths: Reusable and highly efficient.
  - Weaknesses: Performance decreases with thermal cycling.
- Selective Emitters
  - Materials: Photonic crystals and metamaterials.
  - Properties: Tunable spectral emission.
  - Strengths: Customizable for different PV bandgaps.
  - Weaknesses: Expensive and fragile under stress.

4.3. Photovoltaic Cells

- Gallium Antimonide (GaSb)
  - Properties:
    - Bandgap: 0.72 eV.
    - Efficiency: ~30% with optimized emitters.

        - Temperature Tolerance: ~300°C continuous operation.
    - Strengths: Ideal for NIR spectrum and thermal environments.
    - Weaknesses: High cost and limited supply chain.
- Gallium Arsenide (GaAs)
    - Properties:
        - Bandgap: 1.42 eV.
        - Efficiency: ~20–25%.
        - Temperature Tolerance: ~250°C.
    - Strengths: Good durability and broader spectral absorption.
    - Weaknesses: Suboptimal for NIR-centric designs.

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5. Computational Modeling
5.1. Spectral Control Optimization
- Objective: Match emitter spectrum to PV bandgap.
- Tools: COMSOL Multiphysics and MATLAB for thermal and optical simulations.

5.2. System Efficiency
- Objective: Minimize losses and recycle unused radiation.
- Tools: ANSYS for heat transfer and photon recycling simulations.

5.3. Mechanical Durability
- Objective: Model stresses on emitters and PV cells under thermal cycling.
- Tools: FEA to analyze material performance.

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6. System Designs for Reactor Applications
6.1. Compact Microreactors
- Configuration: Direct thermal coupling with tungsten emitters and GaSb PV arrays.
- Advantages: High power density and scalability.

6.2. SMR Integration
- Configuration: Modular emitters and hybrid TPV systems combined with thermoelectrics.
- Advantages: Redundancy and adaptable power output.

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7. Challenges and Proposed Solutions
7.1. High Material Costs
- Challenge: Rare materials increase system cost.
- Solution: Scale production and explore alternative materials (e.g., silicon-based emitters).

7.2. Thermal Degradation
- Challenge: Emitters and filters degrade under extreme temperatures.
- Solution: Introduce ceramic or oxide coatings to extend lifespan.

7.3. Radiation Resistance
- Challenge: Radiation damages PV cells over time.
- Solution: Develop radiation-hardened PV materials like GaN.

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8. Economic Analysis
Cost Breakdown:
- Emitters: $2M–$5M.
- Filters: $1M–$3M.
- PV Cells: $3M–$6M.

Total Estimated Cost: $8M–$14M/MWe, with potential reductions from material innovation.

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9. Future Directions

1. Material Innovations: Develop cost-effective, radiation-resistant emitters and PV cells.
2. Hybrid Systems: Combine TPV with other energy technologies for enhanced efficiency.
3. Demonstration Projects: Deploy TPV systems in pilot SMRs and microreactors.

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10. Conclusion

TPV technology offers a promising solution for integrating high-efficiency, compact power generation systems with nuclear reactors. With advances in material science, system design, and cost reduction, TPV can play a significant role in next-generation nuclear energy solutions.