

# Hybrid Energy Generation: Architecture, Classification, Case Studies and Innovations

Dr.B.Bindu	Vishnukanth S	Aswin B	Thirumalai S	Nagalaxman G	Ashwath N
Dept. Robotics and Automation	Dept. Robotics and Automation	Dept. Robotics and Automation	Dept. Robotics and Automation	Dept. Robotics and Automation	Dept. Robotics and Automation

**Abstract**—As the world grapples with the challenges of climate change and the finite nature of fossil fuels, the quest for sustainable energy sources has never been more urgent. Hybrid power generation systems, which combine multiple renewable energy sources with conventional power generation technologies, offer a promising solution to meet the increasing energy demands while reducing greenhouse gas emissions. This paper provides a comprehensive overview of hybrid power generation systems, highlighting the structure, architecture and potential for a sustainable energy future with hybrid power generation systems. We examine various hybrid system configurations, case studies, and technological advancements that have contributed to the rapid adoption of these systems. The paper concludes by emphasizing the critical role that hybrid systems can play in achieving a cleaner and more sustainable energy landscape.

**Keywords**—Hybrid power generation systems, Renewable energy, Sustainability, Climate change mitigation, Energy transition

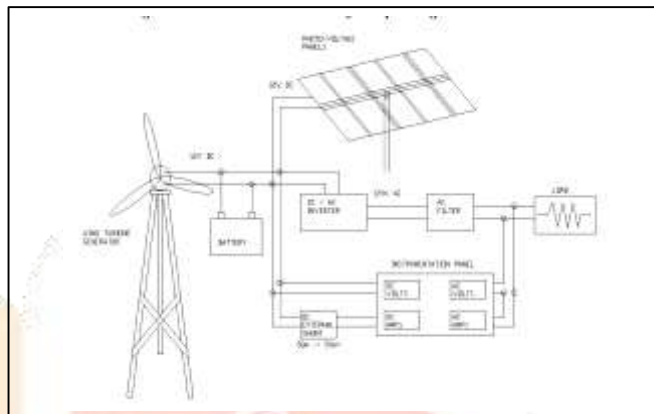


Figure 1: Solar-Wind hybrid power generation system

## I. INTRODUCTION

In today's world, the demand for energy is skyrocketing. As our planet grapples with the consequences of climate change and the finite nature of fossil fuels, finding sustainable ways to produce energy has become paramount. Enter hybrid power generation systems - a solution that's gaining traction and making waves in the world of sustainable energy. In this paper, we're going to take you on a journey through the latest advancements in these hybrid systems, breaking down what they are, what makes them so great, and how they're being used across the globe to create cleaner and more reliable energy.

## II. HYBRID POWER GENERATION SYSTEMS: CONCEPTS AND BENEFITS

### A. Overview of Hybrid Power Generation Systems

#### 1. Definition and Concept:

Hybrid power generation systems are integrated energy systems that combine multiple energy sources to produce electricity or power. These systems are designed to take advantage of the strengths of each energy source while mitigating their individual weaknesses, resulting in more reliable and efficient power generation. The concept of hybrid power generation revolves around the synergy of different energy sources, often combining renewable and non-

renewable sources, to provide a continuous and stable power supply.

The underlying concept of combining multiple energy sources in hybrid power generation systems is driven by several key principles:

- 1. Redundancy and Reliability:** By incorporating multiple energy sources, hybrid systems can maintain power generation even when one source experiences downtime or fluctuations. This redundancy enhances overall system reliability.
- 2. Energy Diversification:** Using a mix of energy sources reduces the system's reliance on a single source, minimizing exposure to fuel price volatility and supply disruptions.
- 3. Enhanced Efficiency:** Different energy sources can complement each other in terms of availability and generation patterns, optimizing overall system efficiency and energy output.
- 4. Environmental Benefits:** Integrating renewable energy sources, such as solar, wind, or hydro, into hybrid systems can reduce greenhouse gas emissions and environmental impact compared to relying solely on fossil fuels.

## 2. Classification of Hybrid Systems:

Hybrid power generation systems can be classified in several ways, depending on various factors. Some common classification criteria include:

### 1. Energy Sources:

- ✓ **Renewable-Non-Renewable Hybrids:** Combining renewable sources like solar, wind, or hydro with non-renewable sources like diesel generators or natural gas turbines.
- ✓ **Renewable-Renewable Hybrids:** Integrating multiple renewable sources, such as solar and wind, to enhance system stability and reliability.
- ✓ **Grid-Battery Hybrids:** Combining grid power with energy storage solutions like batteries for load management, backup, and peak shaving.

### 2. Scale:

- ✓ **Microgrid Hybrids:** Small-scale hybrid systems designed to serve localized communities or facilities, often including solar panels, wind turbines, and energy storage.
- ✓ **Community or Island Hybrids:** Larger hybrid systems that supply power to entire communities or islands, combining various energy sources and storage solutions.
- ✓ **Utility-Scale Hybrids:** Massive hybrid systems designed to feed electricity into the grid, typically combining multiple large power plants, renewables, and energy storage.

### 3. Application:

- ✓ **Residential Hybrids:** Designed for individual homes or small residential complexes, often incorporating solar panels and energy storage.
- ✓ **Commercial/Industrial Hybrids:** Tailored for businesses and industries, integrating solar, wind, or cogeneration systems with backup generators.
- ✓ **Remote Area Hybrids:** Deployed in remote regions lacking access to a reliable grid, using a mix of energy sources to provide power to remote communities or facilities.

### Examples of Different Types of Hybrid Systems:

1. **Solar-Wind Hybrid System:** Combines solar panels and wind turbines to capture energy from both the sun and wind, optimizing power generation throughout the day and night.
2. **Diesel-Solar Hybrid System:** Integrates diesel generators with solar panels and energy storage,

reducing diesel consumption and greenhouse gas emissions in off-grid or unreliable-grid areas.

3. **Hydro-Wind Hybrid System:** Combining hydroelectric power and wind turbines can provide consistent power generation even when wind conditions are variable.
4. **Grid-Battery Hybrid System:** Incorporates grid power and energy storage solutions like lithium-ion batteries to balance supply and demand, reducing peak load from the grid during high-demand periods.
5. **Community Microgrid Hybrid:** A small-scale hybrid system that provides power to a neighborhood by integrating solar, wind, and energy storage to enhance energy reliability and reduce dependence on the central grid.
6. **Cogeneration-Battery Hybrid:** Utilizes combined heat and power (CHP) systems alongside energy storage to efficiently produce both electricity

## B. Components of Hybrid Power Generation Systems

### 1. Primary Energy Sources

#### a. Solar PV (Photovoltaic):

**Key Components of Solar PV Systems:** Solar photovoltaic systems consist of several essential components:

**Solar Panels:** These are composed of photovoltaic cells that convert sunlight into direct current (DC) electricity.

**Inverter:** Converts DC electricity produced by the panels into alternating current (AC) electricity usable in homes and industries.

**Mounting Structure:** Provides support and proper orientation for solar panels.

**Battery (Optional):** Energy storage systems, like batteries, store excess electricity generated during the day for use during the night or when solar generation is low.

**Charge Controller (Optional):** Manages the charging and discharging of batteries in off-grid or hybrid systems.

**Grid Connection (Optional):** In grid-tied systems, solar power can be exported to the grid or drawn from it when needed.

#### Advantages and Limitations of Solar PV in Hybrid Systems:

##### Advantages:

- Abundant and renewable source of energy.
- Low operating and maintenance costs.
- Modular and scalable design.

- Can be integrated into a wide range of hybrid systems.
  - Limitations:
    - Intermittent power generation dependent on sunlight.
    - Energy storage required for night-time or cloudy periods.
    - Initial installation cost (although costs have been decreasing).
    - Limited power generation during adverse weather conditions.
- especially in areas with reliable water sources. Its benefits include:
- ✓ Continuous power generation, regardless of weather conditions.
  - ✓ Acts as a stable baseline power source.
  - ✓ Complements intermittent renewables like solar and wind.

#### d. Fossil Fuels

Integration of Fossil Fuels into Hybrid Systems: Fossil fuels, such as natural gas or diesel, can be integrated into hybrid systems alongside renewable sources or as backup generators. Key considerations include:

- a) **Backup Power:** Fossil fuel generators provide consistent power during renewable energy downtime.
- b) **Cogeneration:** Combined heat and power (CHP) systems use fossil fuels to simultaneously generate electricity and useful heat.
- c) **Transition to Clean Fuels:** Some systems use fossil fuels as a bridge while transitioning to cleaner energy sources.

#### Environmental Considerations and Challenges:

- d) **Emissions:** Fossil fuels release greenhouse gases, contributing to climate change.
- e) **Pollution:** Fossil fuel combustion produces air pollutants harmful to human health.
- f) **Fuel Supply:** Reliance on fossil fuels may be affected by price volatility and supply disruptions.

Hybrid power generation systems leverage these primary energy sources to optimize energy production, balance reliability, and reduce environmental impact based on specific system design and requirements.

## 2) Energy Storage

### a. Batteries

Different Types of Batteries Used in Hybrid Systems: Various types of batteries are used in hybrid systems, each with its own characteristics:

- ✓ **Lead-Acid Batteries:** Commonly used in smaller hybrid systems and vehicles. They are affordable but have lower energy density and shorter lifespan compared to some other types.
- ✓ **Lithium-Ion Batteries:** Widely used due to their high energy density, longer lifespan, and relatively low self-discharge rate. They are suitable for a wide range of hybrid applications.
- ✓ **Flow Batteries:** These batteries use two liquid electrolytes stored in external tanks. They are suitable for large-scale energy storage and offer flexibility in capacity and power output.

## b. Wind Turbines

Working Principle of Wind Turbines: Wind turbines operate based on the principle of converting kinetic energy from wind into mechanical energy and then into electricity.

Key components include:

- ✓ **Blades:** Capture wind energy and start the rotation of the turbine.
- ✓ **Generator:** Converts mechanical energy from the spinning rotor into electrical energy (AC or DC).
- ✓ **Tower:** Supports the rotor and raises it to a sufficient height to capture higher wind speeds.

Integration of Wind Turbines in Hybrid Systems: Wind turbines can be integrated into hybrid systems by combining them with other energy sources like solar or diesel generators. They provide several advantages:

- ✓ Complement solar generation, as wind speeds are often higher at night.
- ✓ Enhance overall system reliability and stability.
- ✓ Wind-diesel hybrids can reduce fuel consumption in off-grid areas.

## c. Hydroelectric

Various Forms of Hydroelectric Power Generation:

Hydroelectric power generation comes in different forms:

- ✓ **Large Hydroelectric Dams:** These utilize the flow of large rivers through dam structures to generate electricity.
- ✓ **Small Hydroelectric Plants:** Typically run-of-river systems that generate power without significant dams, suitable for smaller water bodies.
- ✓ **Tidal and Wave Power:** Capture energy from tides and waves in coastal areas.

Role of Hydroelectric Power in Hybrid Systems: Hydroelectric power can be integrated into hybrid systems,

- ✓ Nickel-Metal Hydride (NiMH) Batteries: Used in some hybrid vehicles, NiMH batteries have a good balance of energy density and longevity.
- ✓ Sodium-Ion Batteries: An emerging technology with potential for large-scale energy storage applications due to the abundance of sodium.

**Role in Energy Storage and Management:** Batteries play a crucial role in energy storage within hybrid systems:

- ✓ They store excess energy generated during periods of high renewable energy production (e.g., sunny or windy days) for later use when energy generation is low.
- ✓ Batteries provide grid stability by supplying power during sudden fluctuations in demand or generation.
- ✓ They enhance the reliability of hybrid systems by acting as backup power sources during energy source failures or outages.

#### b. Flywheels

**Concept of Flywheel Energy Storage:** Flywheel energy storage stores kinetic energy by spinning a rotor (flywheel) at a very high speed within a vacuum or low-friction environment. When electricity needs to be stored, excess energy is used to spin up the flywheel, and when energy is required, the flywheel's kinetic energy is converted back into electricity.

**Advantages and Applications in Hybrid Systems:** Flywheel energy storage offers several advantages:

- ✓ Rapid response time: Flywheels can provide power almost instantaneously, making them suitable for short-duration energy spikes or grid stabilization.
- ✓ Long cycle life: Flywheels can withstand many charge-discharge cycles without significant degradation.
- ✓ High efficiency: They have low energy losses during charge and discharge cycles.

Applications in hybrid systems include:

- ✓ Grid stabilization: Providing frequency regulation and smoothing out power fluctuations.
- ✓ Backup power: Offering quick response in case of sudden outages.
- ✓ Combining with renewable sources: Balancing intermittent generation and enhancing reliability.

#### c. Supercapacitors

**Characteristics of Supercapacitors:** Supercapacitors, also known as ultracapacitors or electric double-layer capacitors (EDLCs), have distinct characteristics:

- ✓ High power density: They can deliver bursts of power quickly.
- ✓ Fast charging and discharging: Supercapacitors can charge and discharge rapidly, making them suitable for applications requiring quick energy transfer.
- ✓ Long cycle life: They can endure a large number of charge-discharge cycles.
- ✓ Lower energy density: Compared to batteries, supercapacitors store less energy for their size.

**Suitability for Energy Storage in Hybrid Systems:** Supercapacitors are well-suited for specific roles within hybrid systems:

- ✓ Buffering power fluctuations: Supercapacitors can absorb and release energy quickly, helping to stabilize grid or system voltage during rapid changes in load or generation.
- ✓ Combining with batteries: Supercapacitors can be paired with batteries to enhance their performance, providing high-power support during transient events.

#### d. Pumped Hydro Storage

**Principle of Pumped Hydro Storage:** Pumped hydro storage is a well-established large-scale energy storage method. It operates by using two water reservoirs at different elevations. During periods of excess electricity generation, surplus power is used to pump water from a lower reservoir to an upper reservoir. When electricity is needed, the stored water is released from the upper reservoir to the lower reservoir, passing through turbines to generate electricity.

**Role in Large-Scale Hybrid Power Generation:** Pumped hydro storage is crucial in large-scale hybrid systems:

- ✓ Grid balancing: It provides a significant capacity for storing excess electricity generated during off-peak hours and supplying it during peak demand.
- ✓ Renewable integration: It helps offset the intermittency of renewable sources like wind and solar by providing dispatchable power when needed.
- ✓ Grid stability: Pumped hydro can respond rapidly to changes in demand, ensuring a stable and reliable electricity supply.

In hybrid power generation systems, the choice of energy storage technology depends on factors such as system scale, desired performance, and cost considerations, with each type of storage fulfilling specific roles in optimizing system operation and efficiency.

### 3) Control and Management Systems

#### a. Power Electronics

**Importance of Power Electronics in Hybrid Systems:** Power electronics play a critical role in hybrid systems by facilitating efficient energy conversion and management. Here's why they are important:

- ✓ **Energy Conversion:** Power electronics devices, such as inverters and converters, are used to transform electrical energy between different forms (e.g., DC to AC) or voltage levels. In hybrid systems, they enable the integration of various energy sources and storage systems that often have different electrical characteristics.
- ✓ **Optimizing Energy Flow:** Power electronics devices allow for precise control of energy flow within the system. For example, they can manage the charging and discharging of batteries, control the speed of generators in hybrid vehicles, or regulate the output of renewable sources like solar panels and wind turbines.
- ✓ **Efficiency:** Power electronics components can improve overall system efficiency by minimizing energy losses during conversion processes. This is crucial for making the most of available energy resources and reducing waste.
- ✓ **Grid Interaction:** In grid-tied hybrid systems, power electronics enable the safe and efficient connection to the electrical grid. They synchronize the system with the grid's frequency and voltage, ensuring smooth energy exchange.

#### b. Control Algorithms

**Algorithms Used for Controlling Hybrid Systems:** Control algorithms are essential for optimizing the operation of hybrid systems. These algorithms vary depending on the specific system and its components. Some common control strategies include:

- ✓ **Energy Management:** Algorithms for deciding when to switch between different energy sources or storage systems to meet load demands efficiently. This includes determining when to use renewables, batteries, or backup generators.
- ✓ **Load Forecasting:** Predictive algorithms can forecast future energy demand, allowing the system to proactively adjust its operation to meet expected requirements.
- ✓ **Grid Interaction:** Control algorithms for grid-connected systems ensure that the system complies with grid regulations, maintains grid stability, and participates in demand response or grid-balancing programs.
- ✓ **Optimization:** Machine learning and AI algorithms can optimize the operation of hybrid systems by analyzing historical data and real-time conditions. They can find the most cost-effective and energy-efficient strategies for energy generation, storage, and consumption.

**Role of Machine Learning and AI in Optimization:** Machine learning and artificial intelligence play a growing role in the optimization of hybrid systems:

- ✓ They can adapt to changing conditions and learn from past performance, making real-time adjustments to improve system efficiency.
- ✓ Advanced machine learning models can predict renewable energy generation, electricity prices, and load demand, enabling better decision-making.
- ✓ AI-driven predictive maintenance can optimize the lifespan and reliability of system components.

#### c. Grid Integration

**Connection to the Electrical Grid:** Grid integration is essential for many hybrid systems, especially those that aim to supply excess energy to the grid or rely on it as a backup power source. The process involves:

- ✓ **Grid Synchronization:** Power electronics components ensure that the system's electrical output matches the grid's frequency and voltage, allowing seamless connection.
- ✓ **Grid Protection:** Safety mechanisms are in place to prevent backfeeding and protect grid workers during maintenance.
- ✓ **Metering and Billing:** Systems connected to the grid often require meters and communication protocols to measure energy flows and enable billing or compensation mechanisms.

**Grid Management and Stability Considerations:** Grid-connected hybrid systems must consider grid management and stability:

- ✓ **Voltage and Frequency Regulation:** The system should help maintain grid stability by providing or absorbing power as needed to balance voltage and frequency.
- ✓ **Grid Codes Compliance:** Compliance with grid codes and regulations ensures the safe and reliable operation of the system within the grid.
- ✓ **Grid Support:** Some hybrid systems can provide ancillary services to the grid, such as frequency regulation or reactive power support, enhancing grid stability.
- ✓ **Grid Disconnect:** In case of grid failures or emergencies, grid-connected hybrid systems often have mechanisms to safely disconnect from the grid and operate independently or switch to backup power sources.

In summary, power electronics, control algorithms, and grid integration are critical components of hybrid systems, enabling efficient energy conversion, optimization, and reliable interaction with the electrical grid. These technologies are essential for achieving the flexibility and performance required for modern hybrid power generation systems.

### C. Integration and Interconnection

1) **System Architecture:** The overall architecture of hybrid power generation systems is designed to seamlessly combine multiple energy sources and components to produce electricity efficiently. Here's an overview:

1. **Energy Sources:** Hybrid systems typically comprise various energy sources such as solar panels, wind turbines, hydroelectric generators, and fossil fuel generators. These sources can be distributed across a geographical area or located in proximity to the energy demand.
2. **Energy Storage:** Energy storage devices like batteries or flywheels are integrated to store excess energy when it's available and release it when needed. They act as a buffer to balance supply and demand.
3. **Power Electronics:** Power electronics components like inverters and converters are crucial for converting and managing the electrical energy between DC and AC, as well as between different voltage levels. They enable compatibility and smooth energy flow between the diverse sources and loads.
4. **Control Systems:** Control algorithms and software are responsible for managing the entire system. They make decisions regarding when to use each energy source, how much energy to store or release, and how to optimize overall system performance.
5. **Grid Interface:** In grid-connected systems, there's a connection to the electrical grid. Power electronics components ensure that the system's electrical output is synchronized with the grid's frequency and voltage. Additionally, metering and communication protocols are established for monitoring and billing purposes.

2) **Electrical Interconnections:** Efficient electrical interconnections between different components are vital for the seamless operation of hybrid power generation systems:

1. **Cabling and Wiring:** Electrical wiring and cables are used to connect the various energy sources, energy storage units, and power electronics components. High-quality wiring is essential to minimize electrical losses during energy transfer.
2. **Busbars:** Busbars are conductive bars or strips used to distribute electrical power within the system. They help in efficiently transmitting electricity from one point to another, reducing resistive losses.
3. **Switchgear and Circuit Breakers:** These components are critical for safety and control. They enable the isolation of components or sections of the system when needed, preventing damage or electrical accidents.
4. **Connectors and Terminals:** High-quality connectors and terminals are used to ensure secure and low-resistance connections between different system elements.
5. **Interconnection Protection:** Protective devices like surge arrestors and fuses safeguard the system

against electrical surges and overcurrent situations, enhancing overall reliability.

Efficient electrical interconnections help minimize energy losses, improve system reliability, and ensure that the generated electricity reaches its intended destination with minimal wastage.

3) **Communication Infrastructure:** Communication systems are essential for monitoring, control, and optimization of hybrid power generation systems:

1. **Data Collection:** Sensors and monitoring devices collect real-time data on energy generation, consumption, system temperatures, and other relevant parameters. This data is crucial for understanding system performance.
2. **Remote Monitoring:** Communication networks allow operators to remotely monitor the system's operation and receive alerts in case of malfunctions or anomalies.
3. **Control and Optimization:** Data collected from the system is used to inform control algorithms and optimization strategies. Machine learning and AI techniques can analyze historical and real-time data to optimize the operation of the hybrid system.
4. **Grid Interaction:** In grid-connected systems, communication infrastructure facilitates communication with the grid operator, enabling grid services like demand response and frequency regulation.
5. **Cybersecurity:** Robust communication networks must also include security measures to protect the system from cyber threats and unauthorized access.

The role of communication systems is to provide the necessary data and control capabilities for system operators and algorithms to make informed decisions, optimize performance, and ensure the reliability of hybrid power generation systems.

### III. CASE STUDY

#### A) Case Study 1: The Texas Clean Energy Project

**Overview:** The Texas Clean Energy Project (TCEP) is a notable example of a hybrid power generation system that integrates various energy sources and carbon capture technology. It is located in Penwell, Texas, and primarily focuses on clean coal technology, although it incorporates multiple energy sources.

#### Components:

- ✓ **Clean Coal:** TCEP employs advanced gasification technology to convert coal into syngas, which is used to produce electricity with lower emissions than traditional coal-fired power plants.
- ✓ **Carbon Capture:** The project incorporates carbon capture and storage (CCS) technology to capture and store carbon dioxide emissions, reducing its environmental impact.
- ✓ **Renewable Energy:** Solar panels and wind turbines are integrated into the system to diversify energy sources and reduce carbon emissions.

Significance: The Texas Clean Energy Project demonstrates the potential for hybrid systems to minimize the environmental impact of fossil fuel-based power generation through the integration of renewable energy and carbon capture technology. It also highlights the importance of reducing greenhouse gas emissions from traditional energy sources.

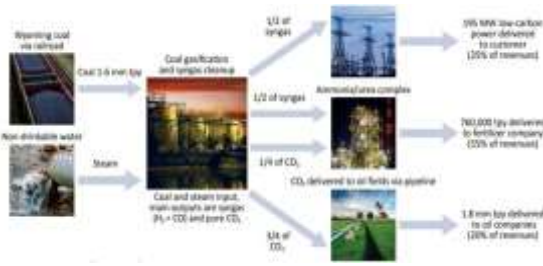


Figure 2: Flow of Texas Clean energy project

B) Case Study 2: The Güssing Model in Austria

Overview: The Güssing Model is a pioneering example of a sustainable and energy-independent community in Güssing, Austria. It serves as a model for transitioning from fossil fuels to renewable energy sources.

Components:

- ✓ Biomass: Güssing primarily relies on biomass resources, including agricultural residues and wood chips, for heating and power generation.
- ✓ Biogas: The community has integrated biogas production from organic waste, contributing to its energy self-sufficiency.
- ✓ Solar and Wind: Güssing also incorporates solar panels and wind turbines to further diversify its energy sources.
- ✓ Energy Efficiency: The model emphasizes energy efficiency measures to reduce overall energy consumption.

Significance: The Güssing Model showcases the potential for local communities to achieve energy independence by integrating multiple renewable energy sources and focusing on energy efficiency. It serves as an inspiration for sustainable development and self-reliance.

C) Case Study 3: The Island Grids of Hawaii

Overview: The island grids of Hawaii represent a challenging environment for energy generation and distribution due to their isolation. These islands have embraced hybrid systems to reduce dependence on imported fossil fuels and harness their abundant renewable resources.

Components:

- ✓ Solar and Wind: Hawaii has extensively deployed solar and wind power to take advantage of its abundant sunshine and trade winds.
- ✓ Energy Storage: Energy storage solutions like lithium-ion batteries are used to store excess renewable energy for nighttime use and to stabilize the grid.

- ✓ Grid Management: Advanced grid management systems enable smooth integration of intermittent renewables and maintain grid stability.
- ✓ Hydroelectric and Geothermal: Some islands also utilize hydroelectric and geothermal power sources for continuous, renewable energy generation.

Significance: The Hawaiian Island grids illustrate the importance of hybrid systems in overcoming energy challenges in isolated regions. They demonstrate the potential for renewable energy and energy storage to reduce reliance on fossil fuels and enhance grid reliability.

D) Case Study 4: The Kasese District in Uganda

Overview: The Kasese District in Uganda represents a rural area that has implemented a hybrid power generation system to provide electricity to off-grid communities.

Components:

- ✓ Hydroelectric Power: Small-scale hydroelectric plants harness the energy of local rivers to generate electricity.
- ✓ Solar PV: Solar panels are used to capture energy from the abundant sunlight.
- ✓ Battery Storage: Energy storage systems, such as batteries, store excess energy for use during nighttime and periods of low generation.
- ✓ Community Microgrids: The district incorporates microgrids to distribute electricity to local communities efficiently.

Significance: The Kasese District case study demonstrates how hybrid systems can bring electricity to remote and off-grid areas, improving living conditions, economic opportunities, and access to education and healthcare. It showcases the adaptability of hybrid systems to meet the unique energy needs of underserved communities.

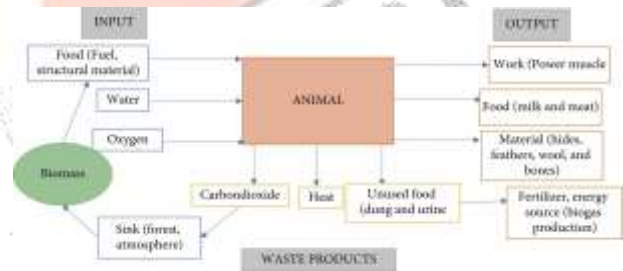


Figure 3: Input-output block for working animals, adapted from Fuller and Aye

These case studies provide valuable insights into the diverse applications and benefits of hybrid power generation systems, showcasing their adaptability to different environments, energy sources, and sustainability goals.

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