Design of rural energy systems

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Abstract. Current focus on rural energy has resulted in the emergence of numerous strategies and a variety of technologies employing different conversion processes and sources. This paper suggests a methodology for finding out the overall first law system efficiency for various routes of energy supply. The method is not an optimisation technique but gives clues regarding the choice of energy sources for maximum overall efficiency of the system. Results indicate that a decentralised system with multi-energy sources is the most efficient (efficiency 12%) for villages.

Keywords. Decentralised energy; centralised energy; combined system; system efficiency.

1. Introduction

The three important elements in an energy system are the source, the task and the conversion device. Efficient energy conversion demands that these three be matched in all respects.

There are four main technical problems which limit the overall efficiency of an energy system, *viz* energy losses through: (i) devices of low overall efficiency (I law), (ii) improper matching of sources and tasks (II law inefficiencies), (iii) adoption of long energy conversion chain routes involving unnecessary energy vectors (steam, compressed air, etc) when shorter routes are available, (iv) long transportation routes when shorter routes or the possibility of elimination of transportation exist.

To overcome these a choice of the most efficient energy system must be made within cost constraints. Rural energy, being a major sector, has been selected for study.

The paper aims at examining the different routes of rural energy conversion with respect to the I law efficiency, transportation routes and energy conversion chains. II law analysis and economic analysis have not been attempted.

2. Energy systems

Modern approaches to the rural energy problem are based on one of the three concepts—the centralised system, the decentralised system and the combined system.

The centralised energy system consists of a nucleus or a few energy nuclei where large amounts of energy of the order of megawatts are generated and transported to wide areas around, *eg*, a coal mine, an oil well, a thermal power plant, a hydroelectric generator, a nuclear reactor and so on. The energy is converted into a 'useful form' like upgraded coal, petroleum oil or electricity, and then transported to the load points.

The decentralised system is characterised by the absence of the large capacity and the

intricate distribution network found in the large energy systems. The systems are mostly renewable and consist of small sources of the order of kilowatts or watts (*eg*, animal powered irrigation, village wood lots, solar photovoltaics, etc) which energise local tasks especially in villages. The small capacity of decentralised systems permit variety and flexibility in the choice of an appropriate system. The elimination of distribution and transportation enable a direct and sometimes thermodynamically better energy conversion route.

In practice, the major fraction of rural energy is of the decentralized type with minor centralised inputs. Such a 'real system' which integrates both concepts is called a combined energy system.

3. System terminology

For the sake of convenience, the decentralised systems are described first, the centralised systems next and the combined systems last. The following common terminology is used for all systems.

System: A village of known population.

Source: The source is the starting point in the energy conversion chain inside the system. Its energy value is called the *source end energy*. Examples of sources are firewood, agrowastes, electricity at load point, direct solar radiation, etc.

External energy source: In the centralised system, the energy in its final state prior to transportation/transmission is taken as the external energy source, *eg*, electricity at the generating point, diesel or kerosene at the refinery, coal at the processing plant, etc. The external energy differs from the source end energy by the transportation/transmission efficiency from the generating point to the system boundaries.

Resource: The source of the centralised system at the starting point is called the resource, for example, coal in mines, crude oil in wells, etc. The energy at this point is called the *resource end energy*.

Secondary energy inputs: In centralised systems, in the production of an energy form, secondary inputs are needed. To produce electricity in a coal thermal plant, inputs such as diesel for firing the boilers and for transportation of coal, human energy in the power plant, etc, are required. Similarly in the transportation of diesel, coal is needed; in the transportation of firewood, coal, human energy and animal energy, etc, are needed. These are referred to as *secondary energy inputs*.

Task: A task is an energy-consuming activity at the end of the conversion chain. The main aim is to provide energy for various tasks.

4. General assumptions

4.1 Resource end, source end and task end energies

Values of energy consumption at the source end and at the task end cannot be added to each other because of the efficiency factors involved between the two. Similarly resource and task end energies are connected by the efficiency factors. Energies have to be added

at common points such as the source or the task end because their values change all along the conversion chain by virtue of the various device conversion efficiencies.

4.2 “Free” and “exerted” energy forms

Sunshine, flow of water, wind, etc, in their natural form are considered free energy inputs and their contributions are not considered in calculations. The contributions of exerted energies like animal power, diesel, wood, etc, which involve expenditure or effort for their harnessing are taken into account.

However, if free rural energies are harnessed by solar collectors, water turbines, windmills, etc, then their contribution becomes valid.

4.3 Sources, tasks and common energy

There are p sources (except in the one source model) and q tasks. The source end energies are S_k (where $k = 1$ to p) and end point energies are T_e (where $e = 1$ to q). The external energies are E_k ($k = 1$ to p) and the resource energies are R_k ($k = 1$ to p). The common energy sources are electricity or biogas.

5. Mathematical formulations of the different models

5.1 Decentralised energy systems

5.1a Common energy mode: In this mode, all sources are used to produce a common intermediate energy form like electricity or biogas. The common energy is supplied to all the rural loads under consideration.

(i) **One source model:** This model assumes a single energy source (S) which is converted into electricity or biogas (E).

The single source may be firewood for electricity (or animal dung for biogas). Generation of E from S involves n energy conversions each of overall efficiency η_i ($i = 1$ to n). The utilisation of E for a task T_i involves m conversions each of overall efficiency η_{ji} ($j = 1$ to m). Figure 1 gives the source-task diagram of the one source, common energy decentralized system.

The overall efficiency of the route $S \rightarrow E \rightarrow T_i$ is

$$\eta_{ol} = \left(\prod_{i=1}^n \eta_i \right) \left(\prod_{j=1}^m \eta_{ji} \right). \quad (1)$$

The source end energy for a task T_i is

$$S_i = T_i (\eta_{ol})^{-1}. \quad (2)$$

The total source end energy for q tasks is

$$S = \left[\sum_{i=1}^q (\eta_{ol})^{-1} T_i \right]. \quad (3)$$

The overall system efficiency is

$$\eta_{o \text{ system}} = \left(\sum T_i \right) (S)^{-1}. \quad (4)$$

Figure 1. Source-task diagram of the one source-common energy-decentralized system (S—source energy, E—common energy, T_e —task energy)

(ii) *Multi-source model:* This model assumes that electricity is generated by numerous sources. Generation of E from a source S_k involves n conversions each of overall efficiency η_{ik} ($i = 1$ to n). The utilisation of E for a task T_j involves m conversions each of overall efficiency η_{ji} ($j = 1$ to m).

Figure 2 gives the source-task diagram of the multi-source, common energy decentralised system.

Figure 2. Source-task diagram of the multi-source-common energy-decentralized system (S_k —source energy, E—common energy, T_e —task energy)

The E generated from a source S_k is

$$E_k = \left[\left(\prod_{i=1}^n \eta_{ik} \right) S_k \right]. \quad (5)$$

The E utilised for a task T_l is

$$E_l = \left[\prod_{j=1}^m (\eta_{jl})^{-1} T_l \right]. \quad (6)$$

Conservation of energy demands that

$$\left(\sum_{k=1}^p E_k \right) = \left(\sum_{l=1}^q E_l \right),$$

i.e.,

$$\sum_{k=1}^p S_k \left(\prod_{i=1}^n \eta_{ik} \right) = \left[\sum_{l=1}^q T_l \left(\prod_{j=1}^m \eta_{jl} \right)^{-1} \right]. \quad (7)$$

The overall system efficiency is

$$\eta_{o \text{ system}} = \left(\sum_{l=1}^q T_l \right) \left(\sum_{k=1}^p S_k \right)^{-1}. \quad (8)$$

5.1b One energy mode: In this mode, a single source provides energy for all tasks without the intermediate conversion into a 'common energy'. The utilisation of S for task T_i involves n conversions each of overall efficiency η_{ii} ($i = 1$ to n).

Figure 3 gives the source-task diagram of the one source decentralised system.

Figure 3. Source-task diagram of the one-source-decentralized system (S —source energy, T_c —task energy)

The overall efficiency of route $S \rightarrow T_i$ is

$$\eta_{oi} = \left(\prod_{i=1}^n \eta_{ii} \right). \quad (9)$$

The source end energy for task T_i is

$$S_i = [(\eta_{oi})^{-1} T_i]. \quad (10)$$

The total source end energy for q tasks is

$$S = \left[\sum_{i=1}^q (\eta_{oi})^{-1} T_i \right]. \quad (11)$$

The overall system efficiency is

$$\eta_{o \text{ system}} = \left(\sum T_i \right) (S)^{-1}. \quad (12)$$

5.1c Multi-energy mode: In this model, the tasks are performed by sources that match it technologically (biogas for cooking, solar electricity for lighting, firewood by producer gas route for pumping, etc). Thermodynamically there may exist a better match but appropriate technology for such energy conversion may not be available.

It is assumed that utilisation of a fraction (S_{ki}) of a source S_k to perform a fraction (T_{ki}) of a task T_e involves n conversions each of overall efficiency η_{iki} ($i = 1$ to n). Figure 4 gives the source-task diagram of the multi-source decentralized system.

The task end energy fraction of task T_i derived from a source k is

$$T_{ki} = S_{ki} \left(\prod_{i=1}^n \eta_{iki} \right). \quad (13)$$

Figure 4. Source-task diagram of the multi-source-decentralized system (S_k —source energy, T_e —task energy)

The total source end energy is

$$\sum_{l=1}^q \sum_{k=1}^p S_{kl} = \left[\sum_{l=1}^q \sum_{k=1}^p T_{kl} \left(\prod_{i=1}^n \eta_{ikl} \right)^{-1} \right]. \quad (14)$$

The overall system efficiency is

$$\eta_{o \text{ system}} = \frac{\sum_{l=1}^q (T_l)}{\sum_{k=1}^p (S_k)} = \frac{\sum_{l=1}^q \left(\sum_{k=1}^p T_{kl} \right)}{\sum_{k=1}^p \left(\sum_{l=1}^q S_{kl} \right)}. \quad (15)$$

5.1d Complex energy mode: This combines the multiple source model of the common energy mode and the multi-energy mode. Some electricity is generated from different sources and used for multiple tasks like pumping, lighting and rural industry. Along with this firewood is used for cooking, etc.

The tasks are separated into electrically energised tasks T_{lx} ($lx = 1$ to q_x) and non-electrical tasks T_{ly} ($ly = 1$ to q_y). Correspondingly the energy sources are subdivided into electricity producing sources S_{kx} ($kx = 1$ to p_x) and non-electricity producing sources, S_{ky} ($ky = 1$ to p_y). To simplify the situation, the system is so chosen that conversion of S_{kx} to T_{ly} and S_{ky} into T_{lx} is not possible. In the electrical system (suffix x), it is assumed that the conversion of source S_{kx} into electricity E_{kx} involves n conversions each of overall efficiency $\eta_{i_1 kx}$ ($i_1 = 1$ to n). The utilisation of electricity E_{lx} for a task T_{lx} involves m conversions each of overall efficiency $\eta_{i_2 lx}$ ($i_2 = 1$ to m). In the non-electrical system (suffix y), it is assumed that the utilisation of a fraction (S_{kly}) of source S_{ky} to perform a fraction (T_{kly}) of a task (T_{ly}) involves n conversions each of overall efficiency η_{ikly} ($i = 1$ to n).

Figure 5 gives the source-task diagram of the complex energy mode, decentralised system.

Conversion of energy at the electricity production point demands that

$$\sum_{kx=1}^{p_x} S_{kx} \left(\prod_{i_1=1}^n \eta_{i_1 kx} \right) = \sum_{lx=1}^{q_x} T_{lx} \left(\prod_{i_2=1}^m \eta_{i_2 lx} \right)^{-1}. \quad (16)$$

The total non-electrical source end energy is

$$\sum_{ky=1}^{p_y} \sum_{ly=1}^{q_y} S_{kly} = \left[\sum_{ky=1}^{p_y} \sum_{ly=1}^{q_y} T_{kly} \left(\prod_{i=1}^n \eta_{ikly} \right) \right]^{-1}. \quad (17)$$

The overall system efficiency is

$$\begin{aligned} \eta_{o \text{ system}} &= \frac{\sum_{l=1}^q T_l}{\sum_{k=1}^p S_k} = \frac{\left(\sum_{lx=1}^{q_x} T_{lx} \right) + \left(\sum_{ly=1}^{q_y} T_{ly} \right)}{\left(\sum_{kx=1}^{p_x} S_{kx} \right) + \left(\sum_{ky=1}^{p_y} S_{ky} \right)} \\ &= \frac{\left[\sum_{lx=1}^{q_x} T_{lx} \right] + \left[\sum_{ly=1}^{q_y} \left(\sum_{ky=1}^{p_y} T_{kly} \right) \right]}{\left[\sum_{kx=1}^{p_x} S_{kx} \right] + \left[\sum_{ky=1}^{p_y} \left(\sum_{ly=1}^{q_y} S_{kly} \right) \right]}. \end{aligned} \quad (18)$$

Figure 5. Source-task diagram of the complex-energy mode-decentralized system (S_k —source energy, E —common energy, T_c —task energy)

5.2 Centralised energy system

5.2a Non-secondary inputs: In this model, secondary inputs associated with the external energy sources are not considered.

A look at figures 1 to 8 indicates that systems described by figures 1 to 5 are closed with respect to import or export of energy. Hence, their overall system efficiency is the ratio of the task end energy to the source end energy. The systems described by figures 6 to 8 import energy from outside. In these cases two types of efficiencies can be considered.

(i) A system efficiency which is the ratio of the task end energy and the source end energy irrespective of the resource system. If electricity is available to the system from a thermal power plant and this is stepped down inside the system (98% efficiency), transmitted at a low voltage (96% efficiency) and used for a motor (70% efficiency) which runs a centrifugal pumpset (60% efficiency), the system efficiency for this sub-system is $98 \times 0.96 \times 0.70 \times 0.60 = 39.51\%$.

(ii) An overall system efficiency which considers the efficiency of the resource system. This is the ratio of the task end energy to the resource end energy. If the electricity from the above sub-system is obtained from coal with the following efficiencies: collection—90%, transport and purification—90%, steam power plant—30%, transmission and distribution till the village entry—90%, then the overall system efficiency is $90 \times 0.90 \times 0.30 \times 0.90 \times 0.3951 = 8.64\%$.

Thus in the centralised and combined systems both system and overall system efficiencies have to be considered to get a clear picture and to know if the loss is in the production or the transit stage or inside the system during conversion.

The following assumptions are made for the centralised energy system:

- (i) Conversion of resource energy R_k to external energy source E_k involves n_3 conversions each of overall efficiency η_{i_3k} ($i_3 = 1$ to n_3).
- (ii) Conversion of E_k to S_k involves m_1 inputs each of magnitude F_{ji} ($j_i = 1$ to m_1).
- (iii) Utilisation of a fraction (S_{kl}) of a source S_k to perform a fraction (T_{kl}) of a task T_l involves n_1 conversions each of overall efficiency η_{i_1kl} ($i_1 = 1$ to n_1).

Figure 6 gives the resource-task diagram of the centralised energy system with no secondary inputs.

The total source end energy is

$$\sum_{l=1}^q \sum_{k=1}^p S_{kl} = \sum_{l=1}^q \sum_{k=1}^p T_{kl} \left(\prod_{i_1=1}^{n_1} \eta_{i_1kl} \right)^{-1}, \quad (19)$$

$$\sum_{k=1}^p \sum_{l=1}^q S_{kl} = \sum_{k=1}^p S_k = \sum_{k=1}^p \left(\prod_{i_2=1}^{n_2} \eta_{i_2k} \right) E_k, \quad (20)$$

$$\sum_{k=1}^p E_k = \sum_{k=1}^p \left(\prod_{i_3=1}^{n_3} \eta_{i_3k} \right) R_k. \quad (21)$$

The total resource energy consumption is

$$\sum_{k=1}^p R_k = \sum_{k=1}^p \left[(S_k) \left(\prod_{i_2=1}^{n_2} \eta_{i_2k} \right)^{-1} \left(\prod_{i_3=1}^{n_3} \eta_{i_3k} \right)^{-1} \right]. \quad (22)$$

Figure 6. Resource-task diagram of the centralized energy system with no secondary inputs (T_c —task energy, S_k —source energy, E_k —intermediate energy, R_k —resource energy)

The system efficiency is

$$\eta_{\text{system}} = \left[\sum_{l=1}^q T_l \right] \left[\sum_{k=1}^p S_k \right]^{-1}. \quad (23)$$

The overall system efficiency is

$$\eta_{\text{osystem}} = \left[\sum_{l=1}^q T_l \right] \left[\sum_{k=1}^p R_k \right]^{-1}. \quad (24)$$

5.2b Secondary inputs considered: The following assumptions are made:

- (i) Conversion of R_k to E_k involves m_2 inputs each of magnitude F_{j_2} ($j_2 = 1$ to m_2).
- (ii) Conversion of E_k to S_k involves m_1 inputs each of magnitude F_{j_1} ($j_1 = 1$ to m_1).

Figure 7 gives the resource-task diagram of the centralised energy system with secondary inputs.

The total secondary input is

$$F = \sum_{k=1}^p \left[\sum_{j_1=1}^{m_1} F_{j_1 k} + \sum_{j_2=1}^{m_2} F_{j_2 k} \right]. \quad (25)$$

The T , S , E and R values are the same as in §5.2a. The system efficiency is

$$\eta_{\text{system}} = \left[\sum_{l=1}^q T_l \right] \left[\sum_{k=1}^p S_k \right]^{-1}. \quad (26)$$

The overall system efficiency is

$$\eta_{\text{osystem}} = \left[\sum_{l=1}^q T_l \right] \left[\left(\sum_{k=1}^p S_k \right) + F \right]^{-1}. \quad (27)$$

Figure 7. Resource-task diagram of the centralized energy system with secondary inputs (T_e —task energy, S_k —source energy, E_k —intermediate energy, R_k —resource energy, F_j —external energy inputs)

5.3 Combined energy system

The suffix y is used for the decentralised energy components (T_{ly} , S_{ly}) and the suffix x for the centralised energy components (T_{lx} , S_{kx} , E_{kx} , R_{kx}).

The following assumptions are made:

- (i) There is no internal generation of electricity.
- (ii) Tasks using external sources of energy and internally generated sources are quite different and do not overlap.
- (iii) Conversion of resource energy R_{kx} to external source E_{kx} involves m_2 conversions each of overall efficiency $\eta_{i_2,kx}$ ($i_2 = 1$ to m_2).
- (iv) Conversion of external source E_{kx} to village source S_{kx} involves m_1 conversions each of overall efficiency $\eta_{i_1,kx}$ ($i_1 = 1$ to m_1).
- (v) Conversion of R_{kx} to E_{kx} involves n_2 inputs each of magnitude F_{j_2} ($j_2 = 1$ to n_2).
- (vi) Conversion of E_{kx} to S_{kx} involves n_1 inputs each of magnitude F_{j_1} ($j_1 = 1$ to n_1).
- (vii) Utilisation of a fraction (S_{kly}) of source S_{kx} to perform a fraction (T_{kly}) of task T_{kx} involving m_1 conversions each of overall efficiency $\eta_{i_1,kl}$ ($i_1 = 1$ to m_1).
- (viii) Utilisation of a fraction (S_{kly}) of source S_{ky} to perform a fraction (T_{kly}) of task T_{ky} involving n conversions each of overall efficiency $\eta_{i_y,kl}$ ($i_y = 1$ to n).

Figure 8 gives the resource-task plus the source-task diagram of the combined energy system with secondary inputs.

The total source energy using internal sources is

$$\sum_{ky=1}^{py} \sum_{ly=1}^{qy} S_{kly} = \sum_{ky=1}^{py} \sum_{ly=1}^{qy} T_{kly} \left[\prod_{i_y=1}^n \eta_{i_y,kl_y} \right]^{-1}. \quad (28)$$

Figure 8. Resource-task + source-task diagram of the combined energy system with secondary inputs (T_e —task energy, S_k —source energy, E_k —intermediate energy, R_k —resource energy, F_j —external energy inputs)

The total source energy using external sources is

$$\sum_{kx=1}^{px} \sum_{lx=1}^{qx} S_{kx} = \sum_{kx=1}^{px} \sum_{lx=1}^{qx} T_{kx} \left[\prod_{lx=1}^m \eta_{lxkx} \right]^{-1}. \quad (29)$$

The total resource energy is

$$\sum_{kx=1}^{px} R_{kx} = \sum_{kx=1}^{px} \left[S_{kx} \left\{ \left(\prod_{i_1=1}^{m_1} \eta_{i_1kx} \right) \left(\prod_{i_2=1}^{m_2} \eta_{i_2kx} \right) \right\}^{-1} \right]. \quad (30)$$

The total secondary input to centralized components is

$$F = \sum_{kx=1}^{px} \left[\sum_{j_1=1}^{n_1} F_{j_1kx} + \sum_{j_2=1}^{n_2} F_{j_2kx} \right]. \quad (31)$$

The system efficiency is

$$\begin{aligned} \eta_{\text{system}} &= \left[\sum_{l=1}^q T_l \right] \left[\sum_{k=1}^p S_k \right]^{-1} \\ &= \left[\sum_{lx=1}^{qx} T_{lx} + \sum_{ly=1}^{qy} T_{ly} \right] \left[\sum_{kx=1}^{px} S_{kx} + \sum_{ky=1}^{py} S_{ky} \right]^{-1}. \end{aligned} \quad (32)$$

The overall system efficiency is

$$\begin{aligned} \eta_{\text{overall system}} &= \left[\sum_{lx=1}^{qx} T_{lx} + \sum_{ly=1}^{qy} T_{ly} \right] \\ &\quad \left[\sum_{kx=1}^{px} R_{kx} + \sum_{ky=1}^{py} S_{ky} + F \right]^{-1}. \end{aligned} \quad (33)$$

6. Identification of rural tasks and sources

By knowing the task end energies from a rural survey, the corresponding source end and resource end energies are determined by using the conversion factors and efficiencies given in this paper. When both the task end and resource end energies are known, the system and the overall system efficiencies are computed.

The first step towards these calculations is to identify rural tasks accurately. These tasks are classified into three groups.

(i) *Type I* (human and animal powered tasks): These comprise a large variety of tasks which are entirely different from each other and are performed sequentially. Replacement of these by mechanisation involves special machines whose operating time is low and expenditure is enormous. Thus these tasks are essentially not substitutable by other energy forms.

(ii) *Type II* (human and animal powered tasks): These are a small number of highly repetitive jobs—that is, repetition of the same type of motion a large number of times, *eg*, pumping water, hand pounding of rice, extraction of oil from coconuts, etc. These tasks can be mechanised.

(iii) *Type III* (fueled by non-living sources of energy): This includes a large set of tasks such as cooking by firewood, lighting by electricity, etc.

Table 1 gives different sources and tasks and also the present and possible future

Table 1a. Present and possible energy systems for rural tasks

Task No.	Task	Human	Animal	Fire-wood (D)	Agro-wastes (D)	Other biomass (D)	Fire-wood (I)	Agro-wastes (I)	Other biomass (I)	Biogas	Coal
<i>l</i>	<i>k</i>	1	2	3	4	5	6	7	8	9	10
1	Transportation (m)	*		+			+		+		
2	Pottery (t)		*	*	*	*	+	+	+	+	*
3	Brickmaking (t)			*	*	*					*
4	Agro-processing (t)			*	*	*	+	+	+	+	*
5	Minor industries (t)			*	*	*	+	+	+	+	*
6	Blacksmithy (t)			*	*	*	+	+	+	+	*
7	Mine & well digging (m)	*	*				+	+	+		
8	Rice milling (m)	*	*				+	+	+		
9	Flour grinding (m)	*	*				+	+	+		
10	Oil extraction (m)	*	*				+	+	+		
11	Pumping (m)	*	*				+	+	+	+	
12	Winnowing (m)	*	*				+	+	+		
13	Minor industries (m)	*	*				+	+	+		
14	Ploughing (m)	*	*				+	+	+		
15	Cooking (t)			*	*	*	+	+	+	*	*
16	Water heating (t)			*	*	*	+	+	+	*	*
17	Lighting (t)						+			*	*
18	Other type II tasks (m)	*	*				+	+	+	*	*

m: mechanical, t: thermal, D: direct conversion, I: indirect conversion, *: present, +: future possibility

Table 1b. Present and possible energy systems for rural tasks

Task No.	Task	Kerosene	Diesel	LPG	Electricity (grid)	Photovoltaics	Solar thermal	Wind	Ethanol	Others
I	'k'	11	12	13	14	15	16	17	18	19
1	Transportation (m)	+	*	+	+				+	
2	Pottery (t)			+	+					
3	Brickmaking (t)				+					
4	Agro-processing (t)			+	+		+			
5	Minor industries (t)			+	+		+			
6	Blacksmithy (t)			+	+					+
7	Mine & well digging (m)	+	+		*					+
8	Rice milling (m)	+	*		*					
9	Flour grinding (m)	+	+		*					
10	Oil extraction (m)	+	+		*					
11	Pumping (m)	+	*		*	+		*	+	
12	Winnowing (m)		+		*					
13	Minor industries (m)	+	*		*	+		*	+	
14	Ploughing (m)		*		*					
15	Cooking (t)	*			*		+			+
16	Water heating (t)	+			*	+			+	+
17	Lighting (t)				*	+			+	+
18	Other type II tasks (m)	*	+		*	+			+	+

m: mechanical, t: thermal, D: direct conversion, I: indirect conversion, *: present, +: future possibility.

energy systems for rural tasks. *Direct* denotes direct combustion and *indirect* denotes usage after conversion into secondary fuels. *Other biomass* denotes casuarina loppings, groundnut shells, toddy leaves, etc., *Firewood (indirect)* includes conversion to charcoal, pyrolytic oil, producer gas, etc. *Agrowastes (indirect)* include conversion to char briquettes, briquettized fuel, pellets, producer gas, etc. *Other biomass (indirect)* refers to briquettes, pellets, producer gas, etc, from thermal and mechanical processes. It also includes wastes which can be incinerated to yield heat. Biogas is from animal dung, human refuse, kitchen waste, water hyacinth and other non-woody biomass.

7. Typical tasks for a large village

In order to get an idea of the magnitude of rural loads, the task end energy is computed from a survey of Muthukur village (population 10,000) in the Nellore District of Andhra Pradesh. The survey was conducted by the author during April–May 1982. Attached to the village are 6896 acres of paddy (80% with 2 crops/year), 415 acres of

Table 2. Energy loads in Muthukur Village on a yearly basis

Task Code No.	Device	P_0 (kW)	N (—)	τ (h)	E_0 ($\times 10^6$ kcal)
1	Labourer (type-II tasks) ⁺	0.08	4600	2400	759.6
2	Cattle (type-II tasks) ⁺⁺	0.36	600	1200	222.9
3	Bullock cart	0.72	674	1200	500.8
4	Ploughing force	0.80	1021	104	73.00
5	Domestic cookstove	0.80	2072	1830	2608.7
6	Hotel cookstove	1.20	2	2700	5.6
7	Bathwater heater	1.40	1288	480	744.4
8	Baker's oven	2.0	1	500	0.9
9	Potter's kiln	18.0	1	72	1.1
10	Brick burning kiln	45.0	1	2200	85.1
11	Blacksmith's furnace	1.67	1	2400	3.4
12	Tobacco curing kiln	4.20	1	125	0.5
13	Oil extracting mill	3.73	1	600	1.9
14	Diesel pumpset	5.97	157	340	274.1
15	Rice mill	33.57	1	4620	133.4
16	Flour mill	3.73	1	4500	14.4
17	Small kerosene lamp	0.0015	2327	1095	3.3
18	Big kerosene lamp	0.003	2215	1450	8.3
19	Domestic electric light	0.04	2306	1095	86.9
20	Fan	0.10	291	730	18.3
21	Street light (Incandescent)	0.10	397	1825	62.3
22	Electric pumpset	3.73	846	290	787.0
23	Tractor	26.11	30	203	136.7
24	Truck	104.4	1	800	71.8
25	Bus	89.5	1	68	5.3

Note: ⁺This includes energy for minedigging -0.03×10^6 kcal; ⁺⁺ Other than ploughing and carting; P_0 : Power output; N : Number of devices; τ : operating time/device/year, E_0 = energy output/year = $(P_0 N \tau)$

sugarcane, 2255 acres of groundnut, 327 acres of casuarina firewood plantation, 85 acres of eucalyptus and 120 acres of chilli plantations. There are nearly 1200 acres of grazing and 500 acres of waste land and 9500 head of cattle. Table 2 gives the energy loads in Muthukur village on a yearly basis.

In devices where the power output varies widely, the average power output is considered (total energy output in one operation/operating time). In rated devices, the most common value is chosen. When the power outputs are different from the values shown in the table, the number of devices equivalent to the rated power are considered, *eg*, if the average power of lamps is 40 W and if there is a 1 kW lamp it is taken as 25 lamps of 40 W. The minor efficiency variations from this change are neglected. When operating time varies, the average number of hours of operation of the standard device is considered, *eg*, if three farmers having 5 HP (3.73 kW) pumpsets operate them for 300, 600, 500 hr/year, the operating time is taken as 467 hr/year/pump.

8. Overall efficiencies used for calculations

Tables 3 to 7 give the overall efficiencies of rural devices for various tasks. The overall efficiency in this constant context is defined as, energy output of device-energy input to device in the form of the given source, for a particular time interval. The efficiencies of rural devices and tasks used in tables 3 to 6 have been computed by Bhatt & Reddy (1982, 1983, 1984). The overall system efficiencies in table 7 have been computed by Bhatt (1984).

The values of the overall efficiencies of rural devices are calculated from efficiencies of individual devices. Some of the useful values are:

Diesel engine: 40%; ethanol engine: 30%; producer gas engine: 30%; biogas engine: 30%; fuel cell: 70%; lead acid battery: 73–87%; steam engine: 20–24%; steam turbine: 35%; gas turbine: 30%; windmill: 6–18%; water wheel: 65%; solar cell: 13%; wood gasifier: 78%; solar flat plate collector: 50%; solar drier: 55%; thermal power plant: 16–25%; electric generator: 80–90%; electric motor: 75–85%; electromechanical coupling: 90–98%.

Some of these efficiencies are dependent on the size of the device. For the purpose of calculations, normal sizes suited for rural use are considered.

Table 3. Overall system efficiencies—transportation

Sources	Transportation (human)	Transportation (goods)	Ploughing
Human	13 ⁽¹⁾	5 ⁽²⁾	3 ⁽³⁾
Bullocks	5 ⁽⁴⁾	5 ⁽⁴⁾	5 ⁽⁵⁾
Diesel	9	9	18
Agrowastes (fuel cells)	18	18	30
Firewood (producer gas)	6	6	13
Firewood (pyrolytic oil)	7	7	14
Ethanol	9	9	18
Electricity (lead acid batteries)	18	18	32

1: bicycle; 2: hand drawn cart; 3: hand drawn plough; 4: carts; 5: bullock drawn plough. The other values in the three columns denote efficiencies of bus, truck and tractor respectively.

Table 4. Overall system efficiencies—Thermal devices

Source	Domestic cooking	Hotel cooking	Bathwater heating	Baking food	Pottery firing	Brick burning	Blacksmithy	Tobacco curing
Firewood (hardwood)	8	5	10	2	14	14	3	1.5
Firewood (twigs & soft woods)	6	4	8	2	12	10	2	1.5
Firewood (producer gas)	46	46	58	5	50	50	15	45
Firewood (charcoal)	3.6	2.0	3.6	1.4	4.5	2.7	0.3	0.3
Firewood (steam generating system)	30	30	—	—	—	—	—	—
Rice husk	16	14	16	3	14	10	1.5	3
Casuarina loppings	—	—	4	—	—	10	—	4
Agro-wastes (char briquettes)	3	2	3	1.2	4.3	2.5	0.3	0.2
Agro-wastes (briquettes)	20	16	20	3	15	14	3	1.5
Agro-wastes (producer gas)	36	36	46	4	42	42	3	42
Other biomass (briquetted fuel)	18	16	18	3	14	14	3	1.5
Biogas	60	60	75	5	60	50	20	45
Solar energy (thermal)	6	4	40	8	—	—	—	30
Solar energy (photovoltaic)	4.2	3.1	7.8	1.4	8.3	8.3	3.1	4.7
Electricity (central grid)	43	40	75	13	80	80	20	15
Kerosene	40	40	40	5	—	—	—	—
LPG	60	50	75	7	—	—	—	—
Coal	20	6	30	12	38	40	1.5	3

Table 5. Overall system efficiencies—mechanical power devices

Sources	Oil extraction	Water pumping	Rice milling	Flour grinding
Human power	3	3	3	3
Bullock power	5	5	5	5
Firewood (producer gas engine)	23	19	24	24
Agro-wastes (producer gas engine)	21	17	21	21
Other biomass (producer gas engine)	23	19	24	24
Biogas (ic engine)	32	30	32	32
Diesel (ic engine)	28	24	30	30
Ethanol (ic engine)	24	20	24	24
Electricity (conventional grid)	30	30	32	28
Solar photovoltaics (electric motor)	3.5	3.5	3.7	3.3
Solar thermal (thermodynamic cycle)	0.1	0.1	0.1	0.1
Windmill (mechanical coupling with energy storage capacity)	4	6	3	3

ic—Indirect combustion

Table 6. Overall system efficiencies—fan and lighting

Source	Domestic fan power	Domestic lighting	Street lighting
Human power (dynamo with fan/bulb)	2.5	0.04	0.04
Animal power (dynamo with fan/bulb)	34	0.05	0.05
Firewood (pyrolytic oil lamp)	—	0.5	0.3
Firewood (natural oil lamp)	—	0.8	0.5
Biogas (mantle)	—	14	12
Ethanol (lantern)	—	0.5	0.3
Kerosene (lantern/pressure lamp)	—	0.01	0.01
Electricity from central grid (bulb/fan)	0.75	1.5 ⁺	1.5 ⁺
		(6)*	(6)*
Solar photovoltaic with storage (fan/bulb)	7	(0.16) ⁺	(0.16) ⁺
		(0.6)*	(0.6)*

⁺ Incandescent lamp, * Fluorescent lamp

Table 8 gives the secondary energy inputs associated with sources external to the village. These values have been computed by Bhatt (1984).

9. Results

9.1 Common energy data (decentralized system)

9.1a *One-source model:* The overall system efficiency (%) for the tasks in table 2 are as follows:

Source—firewood: 3.15; solar photovoltaics: 2.92; rice husk: 2.70; biogas: 5.40.

Table 7. Overall system efficiencies (Source: Bhatt 1984)

Resource	Electricity (<i>in situ</i>)	Electricity ⁺	Diesel ⁺	Kerosene ⁺	LPG ⁺	Coal ⁺
Coal	—	8.7	—	—	—	55
Crude oil at mine	—	14.2	44.5	39	49	—
Hydropotential	—	63	—	—	—	—
Firewood (direct combustion-steam turbine)	13	—	—	—	—	—
Agrowastes (direct combustion-steam turbine)	12	—	—	—	—	—
Other biomass (direct combustion-steam turbine)	12	—	—	—	—	—
Firewood (producer gas-IC engine)	14	—	—	—	—	—
Agrowastes (producer gas-IC engine)	14	—	—	—	—	—
Other biomass (producer gas-IC engine)	12	—	—	—	—	—
Biogas (IC engine)	24	—	—	—	—	—
Ethanol (IC engine)	19	—	—	—	—	—
Solar energy (photovoltaics)	13	—	—	—	—	—

⁺ External source energies; IC—indirect combustion

Table 8. Secondary energy inputs associated with sources external to the village.

Source ⁺ (k)	$\sum_{j_1=1}^{m_1} F_{j_1,k}$ ($\times 10^3$ kcal)	$\sum_{j_2=1}^{m_2} F_{j_2,k}$ ($\times 10^3$ kcal)
Electricity (MWh)	793.1	—
LPG (t)	318.3	1212.3
Kerosene (t)	510.8	508.7
Diesel (t)	447.6	445.8
Coal (t)	404.5	178.2

⁺ at village source end

9.1b Multi-source model: The following sources are assumed (percentages at the source end): firewood—70%; solar photovoltaics—12.5%; agrowastes—5%; biogas—12.5%.

The overall system efficiency for the above tasks is 3.25%.

9.2 One energy mode

If firewood is assumed to be the single energy source the overall system efficiency is 6.92%.

9.3 Multi-energy mode

The percentages of different sources at the source end are: firewood—5.7; agrowastes—9.6; biogas—11.6; animal energy—22.5; human energy—44.2; solar energy—0.003; ethanol—1.3. The overall system efficiency is 11.28%.

9.4a Complex energy mode: The source energy for electrical tasks is solar photovoltaics, rice husk and firewood; and for non-electrical tasks is firewood, biogas, ethanol, rice husk and solar energy. The overall system efficiency is 7.05%.

9.4b Centralized systems: The energy sources are electricity, diesel, coal, kerosene and LPG. The overall system efficiency and the system efficiency considering secondary inputs are 4.06 and 29.80%, and without considering them are 4.09 and 29.98% respectively.

9.4c Combined energy system: The energy source is: non-electrical decentralized components—biogas and rice husk; decentralized electricity producing component—firewood; centralized components—electricity and diesel. The overall system efficiency and the system efficiency are 5.71 and 7.89% respectively.

10. Discussions and conclusions

(i) This paper gives the methodology together with the relevant data for finding out the energy consumption of different rural energy systems. Given the tasks, the energy resources needed for sustaining these can be determined. In the Indian context, no single energy strategy is suited for all conditions. This methodology enables one to find

out the resource energy for any given set of tasks considering the peculiarities of the region. From a knowledge of the current task end energy, the task energy needed ten or twenty years hence can be estimated by forecasting techniques (not discussed here), and from this estimate the energy resources from local and centralized sources needed for the future can be calculated.

It must be mentioned here that this methodology is not an optimisation technique nor does it take economics into consideration; but by using various combinations of sources, tasks, devices and routes, one can arrive at a combination offering high efficiency within the resource and economic constraints.

(ii) The energy problem is so serious that heavy reliance on any one energy form, *eg*, firewood or electricity, will not help. Diversification through multiple source systems has to be reckoned as the only solution to the problem. Multiple source systems involve interaction with various energy departments like the forest departments, electricity boards, thermal or hydropower corporations, etc. This is possible only if there is a framework of the multiple energy system where the resources, sources, tasks, devices and routes are clearly known. The current method enables one to choose the fractions of different resources to be developed for a village so as to energise all tasks in any time horizon. The choice is made by finding out the resource or source end energies for a given set of tasks assuming that they are energised by different energy resources.

(iii) The share of centralised energy to a village could be modified according to its local resource potential. By knowing the available resources (local), the tasks and routes, the decentralised components can be determined. Only the balance need be supplied by the centralised sources.

(iv) The method enables one to have an idea of the magnitudes of the overall system efficiencies of the present day rural energy systems in developing countries. For various other routes, the overall system efficiencies can be determined and improvements if any with them can be compared with the economic inputs needed to install the new systems.

(v) A look at the different energy conversion routes for the same source performing the same tasks suggests ways of conserving energy, *eg*, firewood for domestic cooking through the charcoal route gives 3.6% efficiency whereas through the producer gas pathway gives 46%.

(vi) It is also possible to evaluate the energy conservation that can be achieved by a particular scheme so that its worthiness can be tested, *eg*, electrical energy savings in a model village by the replacement of all existing incandescent lamps by fluorescent tubes.

(vii) The multi-energy mode of the decentralized system is the most efficient system as its efficiency is the highest (11.28%). This is the ideal system for villages.

(viii) Common energy models (electricity, hydrogen, methane, etc.) are infeasible because of low efficiencies and high costs. One energy source models are also infeasible because the energy resources required are nearly ten times more than the village production.

(ix) Centralized systems have low overall system efficiencies but high system efficiencies (< 30%). It is not advisable to utilise the scarce fossil fuels at such low efficiencies. Instead, local alternatives could be developed.

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