Sustainable Energy — without the hot air

Version 3.5.2. December 16, 2008.
This Cover-sheet must not appear in the printed book.
high-resolution edition.

Preface

1 Motivations

2 *The balance sheet*

$\simeq$

$$\text{volume} = \text{flow} \times \text{time}.$$

$$\text{flow} = \frac{\text{volume}}{\text{time}}.$$

$$\text{energy} = \text{power} \times \text{time}.$$

$100/38 \simeq 2.6$

$$\text{kinetic energy} = \frac{1}{2}mv^2.$$

3 Cars

$$\text{energy used per day} = \frac{\text{distance travelled per day}}{\text{distance per unit of fuel}} \times \text{energy per unit of fuel.}$$

33 miles per imperial gallon $\simeq$ 12 km per litre.

$\simeq$

$$8\,\text{kWh per kg} \times 0.8\,\text{kg per litre} \simeq 7\,\text{kWh per litre.}$$

$$\begin{aligned}
\text{energy per day} &= \frac{\text{distance travelled per day}}{\text{distance per unit of fuel}} \times \text{energy per unit of fuel} \\
&= \frac{50\,\text{km/day}}{12\,\text{km/litre}} \times 10\,\text{kWh/litre} \\
&\simeq 40\,\text{kWh/day}.
\end{aligned}$$

4 *Wind*

power per person = wind power per unit area × area per person.

$$2\,\mathrm{W/m^2} \times 4000\,\mathrm{m^2/person} \;=\; 8000\,\mathrm{W\ per\ person},$$

5 Planes

$$\frac{2 \times 240\,000\,\text{litre}}{416\,\text{passengers}} \times 10\,\text{kWh/litre} \simeq 12\,000\,\text{kWh per passenger.}$$

$$\frac{12\,000\,\text{kWh}}{365\,\text{days}} \simeq 33\,\text{kWh/day}.$$

6 *Solar*

$$50\% \times 10\,\mathrm{m}^2 \times 110\,\mathrm{W/m}^2$$

13 kWh per day per person.

$$20\% \times 110\,\mathrm{W/m^2} = 22\,\mathrm{W/m^2}.$$

5 kWh per day per person.

$$
\begin{aligned}
&10\% \times 100\,\text{W/m}^2 \times 200\,\text{m}^2 \text{ per person} \\
\simeq\; &50\,\text{kWh/day/person}.
\end{aligned}
$$

$$10\% \times 100\,\mathrm{W/m^2} = 10\,\mathrm{W/m^2}.$$

$$0.5\,\text{W/m}^2 \times 3000\,\text{m}^2 \text{ per person} = 36\,\text{kWh/d per person.}$$

$\cos\theta \simeq 0.6$

7 *Heating and cooling*

$$4200\,\text{J/litre/}^{\circ}\text{C} \times 110\,\text{litre} \times 40\,^{\circ}\text{C} \;\simeq\; 18\,\text{MJ} \;\simeq\; 5\,\text{kWh}.$$

$21 + 8.5 + 16 \simeq 45$

8 Hydroelectricity

9 *Light*

10 Offshore wind

11 *Gadgets*

13 *Food and farming*

$$170\,\mathrm{kg} \times \frac{3\,\mathrm{kWh/d}}{65\,\mathrm{kg}} \simeq 8\,\mathrm{kWh/d}.$$

15 Stuff

17 *Public services*

18 *Can we live on renewables?*

19 *Every BIG helps*

21 *Smarter heating*

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

average temperature difference × leakiness of building

$$9\,^{\circ}\mathrm{C} \times 7.7\,\mathrm{kWh/d/}^{\circ}\mathrm{C} \simeq 70\,\mathrm{kWh/d}.$$

$$\text{power used} = \frac{9\,^{\circ}\text{C} \times 7.7\,\text{kWh/d/}^{\circ}\text{C}}{0.9} = 77\,\text{kWh/d}.$$

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}.$$

23 *Sustainable fossil fuels?*

24 *Nuclear?*

$$\frac{4.5\,\text{billion tons per planet}}{162\text{ tons uranium per GW-year}} = \text{ 28 million GW-years per planet.}$$

$$2.8 \text{ million GW-years} \;/\; 1600 \text{ years} \;=\; 1750\,\text{GW},$$

$$\begin{aligned} \text{carbon intensity associated with construction} &= \frac{300 \times 10^9\,\text{g}}{10^6\,\text{kW(e)} \times 220\,000\,\text{h}} \\ &= 1.4\,\text{g/kWh(e)}, \end{aligned}$$

25 *Living on other countries' renewables?*

$$84\,\text{MW/h} \times \frac{33\,000\,\text{MW}}{745\,\text{MW}} = 3700\,\text{MW/h},$$

$$10\,\mathrm{GW} \times (5 \times 24\,\mathrm{h}) = 1200\,\mathrm{GWh}.$$

ϵ

$$V = 100\,\text{GWh}/(\rho g h \epsilon),$$

ρ

$\epsilon = 0.9$

27 *Five energy plans for Britain*

29 *What to do now*

$$\frac{1}{5} \times 10\% \times 9000\,\mathrm{m}^2 \times 2\,\mathrm{W/m}^2 = 360\ \mathrm{W/m}^2$$

$$5\,\mathrm{W/m^2} \times 450\,\mathrm{m^2} = 54\,\mathrm{kWh/d}\ \text{per person}.$$

31 *The last thing we should talk about*

A Cars II

$$\text{kinetic energy} = \frac{1}{2}mv^2.$$

$$\frac{1}{2}mv^2 \simeq 390\,000\,\text{J} \simeq 0.1\,\text{kWh}.$$

$$\frac{\text{kinetic energy}}{\text{time between braking events}} = \frac{\frac{1}{2}m_{\text{c}}v^2}{d/v} = \frac{\frac{1}{2}m_{\text{c}}v^3}{d}, \tag{A.1}$$

c_d

$c_d A_{car}$

$$\text{mass} = \text{density} \times \text{volume}$$

ρ

$m_{\text{air}} = \rho A v t$

ρ

$$\frac{1}{2}m_{\text{air}}v^2 = \frac{1}{2}\rho A v t\, v^2,$$

$$\frac{\frac{1}{2}\rho A v t v^2}{t} = \frac{1}{2}\rho A v^3.$$

$$\begin{aligned} \text{power going into brakes} \quad &+ \quad \text{power going into swirling air} \\ = \tfrac{1}{2} m_{\mathrm{c}} v^3 / d \quad &+ \quad \tfrac{1}{2} \rho A v^3. \end{aligned} \tag{A.2}$$

$$(m_c/d)\,/(\rho A)\,.$$

$$m_c > \rho A d.$$

$\rho A d$

$$A_{\text{car}} = 2\,\text{m wide} \times 1.5\,\text{m high} = 3\,\text{m}^2$$

$c_d = 1/3$

$$d^* = \frac{m_\mathrm{c}}{\rho c_\mathrm{d} A_\mathrm{car}} = \frac{1000\,\mathrm{kg}}{1.3\,\mathrm{kg/m^3} \times \frac{1}{3} \times 3\,\mathrm{m^2}} = 750\,\mathrm{m}.$$

$$\text{total power of car} \simeq 4\left[\frac{1}{2}m_{\mathrm{c}}v^3/d + \frac{1}{2}\rho A v^3\right].$$

$A = c_{\mathrm{d}} A_{\mathrm{car}} = 1$

$$4 \times \frac{1}{2}\rho A v^3 = 2 \times 1.3\,\mathrm{kg/m^3} \times 1\,\mathrm{m^2} \times (31\,\mathrm{m/s})^3 = 80\,\mathrm{kW}.$$

$$4 \times \frac{1}{2}\rho A v^3,$$

$$\text{energy per distance } = 4 \times \frac{1}{2}\rho A v^2.$$

ρ

$$A = c_\mathrm{d} A_\mathrm{car}$$

$4 \times \frac{1}{2}\rho A v^2$

$4 \times \frac{1}{2}\rho A v^2$

ρ

$$\frac{\text{energy per distance of bike}}{\text{energy per distance of car}} = \frac{c_{\text{d}}^{\text{bike}} A_{\text{bike}} v_{\text{bike}}^2}{c_{\text{d}}^{\text{car}} A_{\text{car}} v_{\text{car}}^2}.$$

$$\frac{A_{\text{bike}}}{A_{\text{car}}} = \frac{1}{4}.$$

$$\frac{c_{\mathrm{d}}^{\mathrm{bike}}}{c_{\mathrm{d}}^{\mathrm{car}}} = \frac{1}{1/3}$$

$$\frac{v_{\text{bike}}}{v_{\text{car}}} = \frac{1}{5}.$$

$$
\begin{aligned}
\frac{\text{energy-per-distance of bike}}{\text{energy-per-distance of car}} &= \left(\frac{c_{\text{d}}^{\text{bike}}}{c_{\text{d}}^{\text{car}}} \frac{A_{\text{bike}}}{A_{\text{car}}} \right) \left(\frac{v_{\text{bike}}}{v_{\text{car}}} \right)^2 \\
&= \left(\frac{3}{4} \right) \times \left(\frac{1}{5} \right)^2 \\
&= \frac{3}{100}
\end{aligned}
$$

$c_d A_{car} = 1$

$c_{\mathrm{d}} A_{\mathrm{train}} = 11$

$$\text{force} \times \text{velocity} \;=\; (100 \text{ newtons}) \times (31\,\text{m/s}) \;=\; 3100 \text{ W/m}^2;$$

$$C_{\mathrm{rr}} m_{\mathrm{c}} g = \frac{1}{2} \rho c_{\mathrm{d}} A v^2,$$

$$v = \sqrt{2\frac{C_{\mathrm{rr}} m_{\mathrm{c}} g}{\rho c_{\mathrm{d}} A}} = 7\,\mathrm{m/s} = 16\,\text{miles per hour}.$$

$$v = 33\,\mathrm{m/s} = 74\,\text{miles per hour}.$$

$$v = 12\,\mathrm{m/s} = 26\,\text{miles per hour}.$$

$c_d A = 0.3\,\mathrm{m}^2$

B *Wind II*

ρ

$$\text{mass} = \text{density} \times \text{volume}$$

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho Avt\, v^2 = \frac{1}{2}\rho Atv^3. \tag{B.1}$$

$$\frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho A v^3. \tag{B.2}$$

$$\frac{1}{2}\rho v^3 = \frac{1}{2} 1.3\,\mathrm{kg/m^3} \times (6\,\mathrm{m/s})^3 = 140\,\mathrm{W/m^2}. \tag{B.3}$$

$$
\begin{aligned}
& \text{efficiency factor} \times \text{power per unit area} \times \text{area} \\
= \; & 50\% \times \frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 && \text{(B.4)} \\
= \; & 50\% \times 140\,\text{W/m}^2 \times \frac{\pi}{4} (25\,\text{m})^2 && \text{(B.5)} \\
= \; & 34\,\text{kW}. && \text{(B.6)}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\text{power per windmill (B.4)}}{\text{land area per windmill}} &= \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} && \text{(B.7)} \\
&= \frac{\pi}{200} \frac{1}{2} \rho v^3 && \text{(B.8)} \\
&= 0.016 \times 140\,\mathrm{W/m^2} && \text{(B.9)} \\
&= 2.2\,\mathrm{W/m^2}. && \text{(B.10)}
\end{aligned}
$$

$(4/6)^3 \simeq 0.3$

$$v(z) = v_{10} \left(\frac{z}{10\,\mathrm{m}} \right)^{\alpha},$$

$$v(z) = v_{\text{ref}} \frac{\log(z/z_0)}{\log(z_{\text{ref}}/z_0)},$$

C Planes II

$$\text{force} = \text{rate of change of momentum}, \tag{C.1}$$

$$\text{force exerted on A by B} = -\text{ force exerted on B by A.} \tag{C.2}$$

$$m_{\text{sausage}} = \text{density} \times \text{volume} = \rho v t A_{\text{s}}. \tag{C.3}$$

$$\text{mass} \times \text{velocity} = m_{\text{sausage}} u = \rho v t A_{\text{s}} u. \tag{C.4}$$

$$mgt. \tag{C.5}$$

$$\rho v t A_s u = mgt, \tag{C.6}$$

$$u = \frac{mg}{\rho v A_\mathrm{s}}.$$

$$
\begin{aligned}
P_{\text{lift}} &= \frac{\text{kinetic energy of sausage}}{\text{time}} && \text{(C.7)}\\
&= \frac{1}{t}\frac{1}{2}m_{\text{sausage}}u^2 && \text{(C.8)}\\
&= \frac{1}{2t}\rho v t A_{\text{s}}\left(\frac{mg}{\rho v A_{\text{s}}}\right)^2 && \text{(C.9)}\\
&= \frac{1}{2}\frac{(mg)^2}{\rho v A_{\text{s}}}. && \text{(C.10)}
\end{aligned}
$$

$$
\begin{aligned}
P_{\text{total}} &= P_{\text{drag}} + P_{\text{lift}} && \text{(C.11)} \\
&= \frac{1}{2} c_{\text{d}} \rho A_{\text{p}} v^3 + \frac{1}{2} \frac{(mg)^2}{\rho v A_{\text{s}}}, && \text{(C.12)}
\end{aligned}
$$

$$\left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{P_{\text{total}}}{v} = \frac{1}{2}c_{\text{d}}\rho A_{\text{p}}v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_{\text{s}}}, \tag{C.13}$$

$\frac{1}{2}c_{\mathrm{d}}\rho A_{\mathrm{p}}v^2$

$$\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_s}$$

$\frac{1}{2}c_\mathrm{d}\rho A_\mathrm{p}v^2$

$$\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}$$

$\rho = 0.41$

$\epsilon = 1/3$

$$\frac{\text{energy}}{\text{distance}} = \frac{1}{\epsilon}\left(\frac{1}{2}c_{\text{d}}\rho A_{\text{p}}v^2 + \frac{1}{2}\frac{(mg)^2}{\rho v^2 A_{\text{s}}}\right). \tag{C.14}$$

$\frac{1}{2}c_{\mathrm{d}}\rho A_{\mathrm{p}}v^2$

$$\frac{1}{2}\frac{(mg)^2}{\rho v^2 A_\mathrm{s}}$$

$$c_{\mathrm{d}}\rho A_{\mathrm{p}}v^2 = \frac{(mg)^2}{\rho v^2 A_{\mathrm{s}}}, \tag{C.15}$$

$$\rho v_{\mathrm{opt}}^2 = \frac{mg}{\sqrt{c_{\mathrm{d}} A_{\mathrm{p}} A_{\mathrm{s}}}}, \tag{C.16}$$

ϵ

ρ

$$\begin{aligned}
\text{force} &= \left.\frac{\text{energy}}{\text{distance}}\right|_{\text{ideal}} = \frac{1}{2} c_{\mathrm{d}} \rho A_{\mathrm{p}} v^2 + \frac{1}{2} \frac{(mg)^2}{\rho v^2 A_{\mathrm{s}}} && \text{(C.17)} \\
&= c_{\mathrm{d}} \rho A_{\mathrm{p}} v_{\mathrm{opt}}^2 && \text{(C.18)} \\
&= c_{\mathrm{d}} \rho A_{\mathrm{p}} \frac{mg}{\rho (c_{\mathrm{d}} A_{\mathrm{p}} A_{\mathrm{s}})^{1/2}} && \text{(C.19)} \\
&= \left(\frac{c_{\mathrm{d}} A_{\mathrm{p}}}{A_{\mathrm{s}}} \right)^{1/2} mg. && \text{(C.20)}
\end{aligned}$$

$$f_A = \frac{A_\mathrm{p}}{A_\mathrm{s}}. \tag{C.21}$$

$$\text{force} = (c_{\text{d}} f_A)^{1/2}(mg). \tag{C.22}$$

$c_\mathrm{d} \simeq 0.03$

$f_A \simeq 0.04$

$$(c_\mathrm{d} f_A)^{1/2}\, mg = 0.036\, mg = 130\,\mathrm{kN}. \tag{C.23}$$

$1/\epsilon$

ϵ

$$\text{transport cost} = \frac{1}{\epsilon}\frac{\text{force}}{\text{mass}} \tag{C.24}$$

$$= \frac{1}{\epsilon}\frac{(c_{\mathrm{d}} f_A)^{1/2} mg}{m} \tag{C.25}$$

$$= \frac{(c_{\mathrm{d}} f_A)^{1/2}}{\epsilon} g. \tag{C.26}$$

$\epsilon = 1/3$

$0.15\,g$

0.4 kWh/ton-km.

c_{d}

$0.45\,g,$

$$
\begin{aligned}
&\text{transport efficiency (passenger–km per litre of fuel)} \\
&= \text{number of passengers} \times \frac{\text{energy per litre}}{\frac{\text{thrust}}{\epsilon}} && \text{(C.27)} \\
&= \text{number of passengers} \times \frac{\epsilon \times \text{energy per litre}}{\text{thrust}} && \text{(C.28)} \\
&= 400 \times \frac{1}{3} \frac{38\,\text{MJ/litre}}{200\,000\,\text{N}} && \text{(C.29)} \\
&= 25\,\text{passenger–km per litre} && \text{(C.30)}
\end{aligned}
$$

$$\text{range} = v_{\text{opt}} \frac{\text{energy}}{\text{power}} = \frac{\text{energy} \times \epsilon}{\text{force}}. \tag{C.31}$$

$$\text{range} = \frac{\text{energy}\,\epsilon}{\text{force}} = \frac{Cm\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}(mg)} = \frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}} \frac{C}{g}. \tag{C.32}$$

$$\left(\frac{\epsilon f_{\text{fuel}}}{(c_{\text{d}} f_A)^{1/2}}\right)$$

$$\frac{C}{g},$$

$$d_{\text{Fuel}} = \frac{C}{g} = 4000\,\text{km}. \tag{C.33}$$

$$\left(\frac{\epsilon f_{\mathrm{fuel}}}{(c_{\mathrm{d}} f_A)^{1/2}} \right)$$

$\epsilon = 1/3$

$(c_{\mathrm{d}} f_A)^{1/2} \simeq 1/20$

$v^2 \sim 1/\rho$

$v^2 \sim mg/(\rho(c_d A_p A_s)^{1/2})$

$0.4\,\text{kWh/ton-km}$.

0.4 kWh/ton-km,

$$\frac{(c_{\mathrm{d}} f_A)^{1/2}}{\epsilon} g, \tag{C.34}$$

ϵ

ρ

$m_{\text{total}} = \rho V$

$$F = \frac{1}{2} c_{\mathrm{d}} A \rho v^2, \tag{C.35}$$

c_{d}

ϵ

$$\frac{F}{\epsilon m_{\text{total}}} = \frac{\frac{1}{2}c_{\text{d}}A\rho v^2}{\epsilon\rho\frac{2}{3}AL} \tag{C.36}$$

$$= \frac{3}{4\epsilon}c_{\text{d}}\frac{v^2}{L} \tag{C.37}$$

ρ

ϵ

$$\frac{F}{\epsilon m_{\text{total}}} = 3 \times 0.03 \frac{(22\,\text{m/s})^2}{400\,\text{m}} = 0.1\,\text{m/s}^2 = 0.03\,\text{kWh/t-km}.$$

$\epsilon = 1/3$

D Solar II

E Heating II

$$\text{power loss} = \text{area} \times U \times \text{temperature difference.}$$

$$u_{\text{series combination}} = 1 \Bigg/ \left(\frac{1}{u_1} + \frac{1}{u_2} \right) .$$

$$\begin{aligned} \begin{matrix}\text{power}\\(\text{watts})\end{matrix} &= C\frac{N}{1\,\text{h}}V(\text{m}^3)\Delta T(\text{K}) && \text{(E.1)}\\ &= (1.2\,\text{kJ}/\text{m}^3/\text{K})\frac{N}{3600\,\text{s}}V(\text{m}^3)\Delta T(\text{K}) && \text{(E.2)}\\ &= \frac{1}{3}NV\Delta T. && \text{(E.3)} \end{aligned}$$

$$\text{energy loss} = \text{area} \times U \times (\Delta T \times \text{duration}),$$

$$\frac{1}{3}NV \times (\Delta T \times \text{duration}).$$

$$\text{Something} \times (\Delta T \times \text{duration}),$$

$$\text{energy lost} = \text{leakiness} \times \text{temperature demand.}$$

$$\text{energy consumed} = \text{energy delivered/coefficient of performance.}$$

$3.7\,\mathrm{W}/^{\circ}\mathrm{C}/\mathrm{m}^2$.

$$322\ \mathrm{W/m^2/^\circ C} \times 120\,\text{degree-hours} \simeq 39\,\mathrm{kWh}.$$

155 kWh/d.

$$7.7\,\text{kWh/d/}^\circ\text{C} \times 2866\,\text{degree-days/y}/(365\,\text{days/y}) = 61\,\text{kWh/d}.$$

$$1 \bigg/ \left(\frac{1}{2.2} + \frac{1}{1.7} \right) \simeq 1\,\mathrm{W/m^2/K}.$$

$$\text{efficiency} = \frac{T_2}{T_2 - T_1}.$$

$$\text{efficiency} = \frac{T_2}{T_1 - T_2}.$$

$\rho = 2750$

$$\begin{aligned}\text{mass} &= \frac{\text{energy}}{\text{heat capacity} \times \text{temperature difference}} \\ &= \frac{24 \times 30 \times 3.6\,\text{MJ}}{(820\,\text{J/kg/}^\circ\text{C})(50\,^\circ\text{C} - 16\,^\circ\text{C})} \\ &= 100\,000\,\text{kg},\end{aligned}$$

$$\frac{1}{\sqrt{4\pi\kappa t}} \exp\left(-\frac{x^2}{4(\kappa/(C\rho))t}\right)$$

ρ

$$\sqrt{2\frac{\kappa}{C\rho}t};$$

$\rho = 2500$

$\rho = 1000$

$$5\,\text{W/m}^2 \times 160\,\text{m}^2 = 800\ \text{W/m}^2 = 19\,\text{kWh/d per person.}$$

$$\text{Flux} = \kappa \times \frac{\Delta T}{h} = 3\,\text{W/m}^2.$$

$$\frac{\partial T(z,t)}{\partial t} = \frac{\kappa}{C_\mathrm{V}} \frac{\partial^2 T(z,t)}{\partial z^2}. \tag{E.4}$$

$$T(0, t) = T_{\text{surface}}(t) = T_{\text{average}} + A\cos(\omega t), \tag{E.5}$$

$$T(z,t) = T_{\text{average}} + A\, e^{-z/z_0} \cos(\omega t - z/z_0), \tag{E.6}$$

$$z_0 = \sqrt{\frac{2\kappa}{C_\mathrm{V}\omega}}. \tag{E.7}$$

$$\kappa \frac{\partial T}{\partial z} = \kappa \frac{A}{z_0} \sqrt{2} e^{-z/z_0} \sin(\omega t - z/z_0 - \pi/4). \tag{E.8}$$

$$\kappa \frac{A}{z_0} \sqrt{2} = A \sqrt{C_V \kappa \omega}. \tag{E.9}$$

F *Waves II*

$$v = \frac{gT}{2\pi},$$

$$P_{\text{potential}} \simeq m^* g \bar{h} / T, \tag{F.1}$$

$\frac{1}{2}\rho h(\lambda/2)$

$$P_{\text{potential}} \simeq \frac{1}{2}\rho h \frac{\lambda}{2} g h / T. \tag{F.2}$$

$$P_{\text{potential}} \simeq \frac{1}{4}\rho g h^2 v. \tag{F.3}$$

$$P_{\text{total}} \simeq \frac{1}{2}\rho g h^2 v. \tag{F.4}$$

$$P_{\text{total}} = \frac{1}{4}\rho g h^2 v. \tag{F.5}$$

$$P_{\text{total}} = \frac{1}{4}\rho g h^2 v = 40\,\text{kW/m}. \tag{F.6}$$

G *Tide II*

$\rho \times (2h)$

ρ

$$\frac{2\rho h g h}{6\,\text{hours}},$$

$$\text{power per unit area of tide-pool} \simeq 3\,\text{W/m}^2.$$

$$\rho g^{3/2}\sqrt{d}h^2/2. \tag{G.1}$$

$\rho g^{3/2}\sqrt{d}h^2/2$

$$v = \sqrt{gd}. \tag{G.2}$$

$$U = vh/d. \tag{G.3}$$

$$K_{\mathrm{BV}} = \frac{1}{2}\rho A U^3, \tag{G.4}$$

$$\frac{1}{4}\rho g h^2 \lambda. \tag{G.5}$$

$$\text{power} = \frac{1}{2}(\rho g h^2 \lambda) \times w/T = \frac{1}{2}\rho g h^2 v \times w, \tag{G.6}$$

$$\text{power} = \rho g h^2 \sqrt{gd} \times w/2 = \rho g^{3/2} \sqrt{d} h^2 \times w/2. \tag{G.7}$$

$$K_{\mathrm{BV}} = \frac{1}{2}\rho A U^3 = \frac{1}{2}\rho w d (vh/d)^3 = \rho \left(g^{3/2}/\sqrt{d} \right) h^3 \times w/2. \tag{G.8}$$

$$\frac{K_{\mathrm{BV}}}{\text{power}} = \frac{\rho w \left(g^{3/2}/\sqrt{d}\right) h^3}{\rho g^{3/2} h^2 \sqrt{d} w} = \frac{h}{d}. \tag{G.9}$$

$h \sim 1/d^{1/4}$

$$\frac{\text{power per tidemill}}{\text{area per tidemill}} = \frac{\pi}{200}\frac{1}{2}\rho U^3.$$

$\frac{\pi}{200}\frac{1}{2}\rho U^3$

$R_1 \rho U^2$

$R_1 \rho U^3$

$R_1 \rho U^3$

$\epsilon_g = 0.9$

$\epsilon_{\mathrm{p}} = 0.85$

$$b/\epsilon_p = \epsilon_g(b + 2h).$$

$\epsilon = \epsilon_g \epsilon_p$

$$b = 2h\frac{\epsilon}{1-\epsilon}.$$

$\epsilon = 76\%$

$$\left(\frac{1}{2}\rho g\epsilon_{\mathrm{g}}(b+2h)^2-\frac{1}{2}\rho g\frac{1}{\epsilon_{\mathrm{p}}}b^2\right)\Bigg/\,T,$$

$\epsilon_{\mathrm{g}} 2\rho g h^2 / T$

$$\left(\frac{1}{1-\epsilon}\right),$$

H *Stuff II*

I *Quick reference*

$\simeq$

$\simeq 10^5$

$\simeq \pi \times 10^7$

$\simeq 0.37g$

$\simeq$

J *Populations and areas*

K UK energy history