Engineering Tripos, Part IB **April 2014**

Paper 8: Mechanical Engineering Elective

Renewable Energy Systems

Life Cycle Analysis and Energy Payback

Michael Sutcliffe, Hugh Shercliff, Mike Ashby
CUED/Granta Design

Outline

- Revision:
  - Product life cycles
  - Life cycle assessment (LCA)
  - Cambridge Engineering Selector (CES) "Eco" data

- Application to wind turbine systems

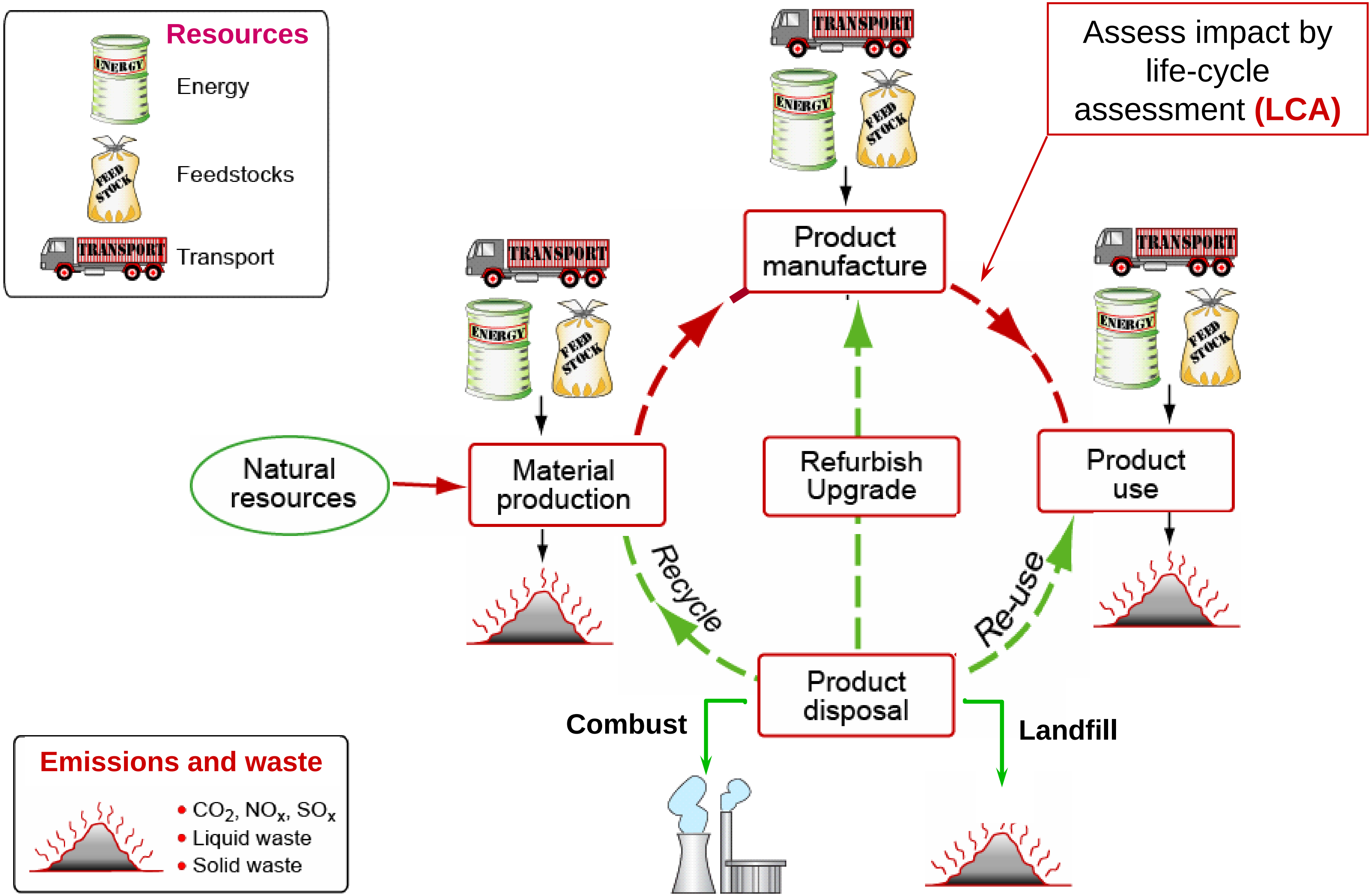
- Estimating energy payback period

- Case studies:
  - effect of machine scale
  - onshore vs. offshore systems

More info on LCA for products:

- Ashby M.F., "**Materials Selection in Mechanical Design**", **Chapter 16**
- Ashby M.F., Shercliff H.R. and Cebon D., "**Materials: Engineering, Science, Processing and Design**", **Chapter 20**
- Ashby M.F., "**Materials and the Environment**"

The product life-cycle



Resources

- Energy
- Feedstocks
- Transport

Assess impact by life-cycle assessment **(LCA)**

Natural resources

Material production

Product manufacture

Product use

Refurbish Upgrade

Product disposal

Recycle

Re-use

Combust

Landfill

Emissions and waste

- CO_2, NO_x, SO_x
- Liquid waste
- Solid waste

Life cycle assessment (LCA)

- Increasingly, all products must be assessed for their full life cycle environmental impact (e.g. various ISO standards)
- **Life cycle assessment** (LCA): quantifies the inputs and impacts at each of the four stages: ***production, manufacture, use, disposal***

Typical LCA outputs:

- Energy consumption over life
- Water consumption
- Emission of CO_2, NO_x, SO_x etc
- Particulates
- Toxic residues
- More …….

+ various methodologies to merge these into a single "**eco-indicator**"

Simplified LCA strategy: adopt a *single measure* of environmental impact

Simplified LCA

Guidance on appropriate single measure of impact?

(1) Kyoto Protocol (1997): international agreement to reduce greenhouse gases

(2) IPCC report (2007): identifies carbon as principal cause of climate change

(3) Draft EU directive 2003/0172: *"On establishing a framework for the setting of Eco-design requirements for Energy-using Products (EuPs)"*

- Manufacturers of EuPs shall demonstrate that "they have considered the use of energy in their products as it relates to:
  - Materials
  - Manufacture
  - Packaging, transport, distribution and use
  - End of life"
- "Steps to minimise energy consumption shall be identified".

Hence a practical solution: use **CO_2** or **Energy**

- These are closely related, and also reasonably understood by the public.

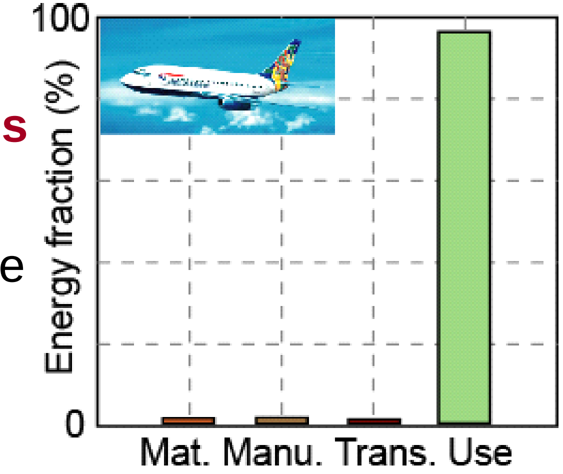
Examples: energy consumption of products

Which life phase dominates?

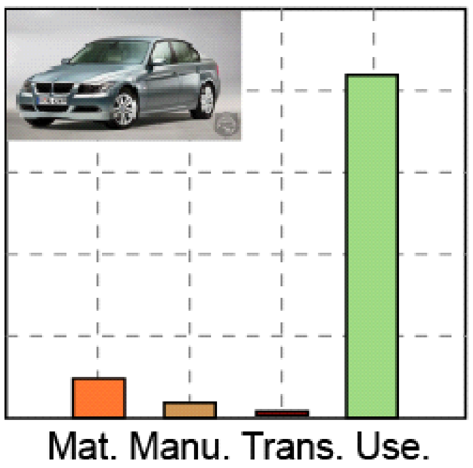
Examples of EuPs

Use phase dominant

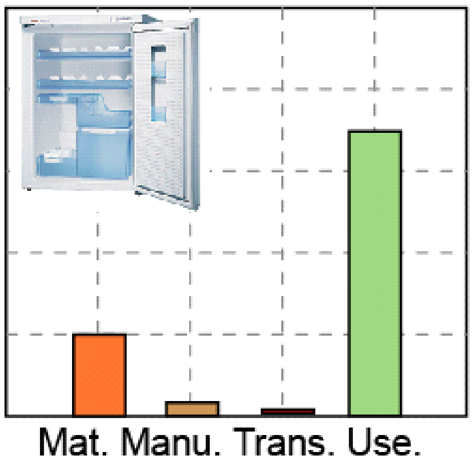
Civil aircraft



Family car



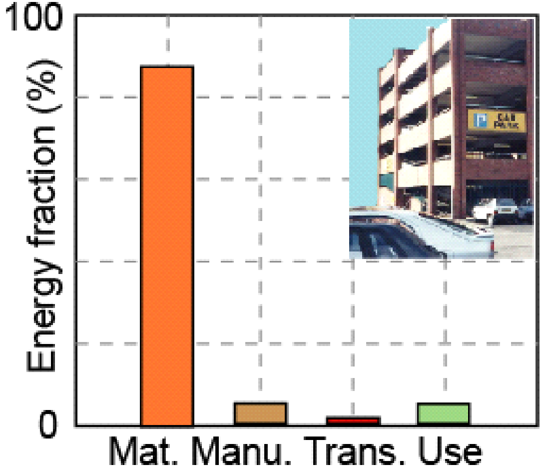
Appliance (refrigerator)



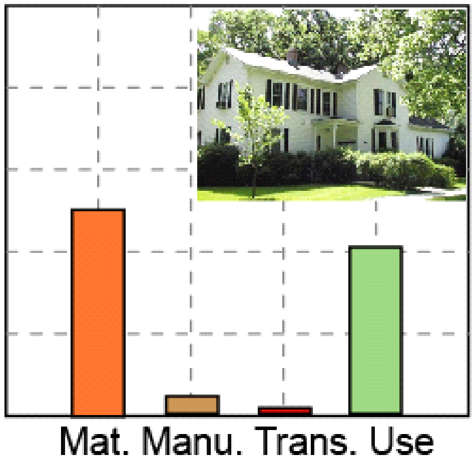
Other products

A more mixed picture

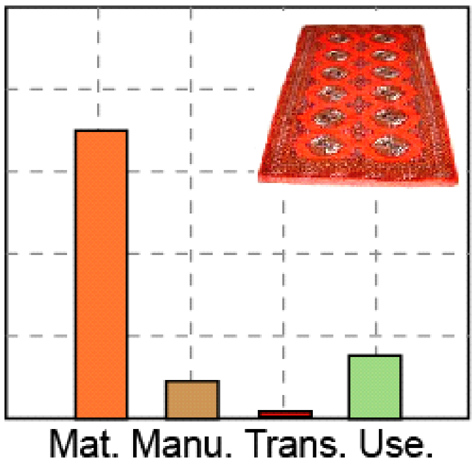
Multi-storey car park



Private house



Fibers (Carpet)



Inputs to LCA: simple example

Example product: milk container

LIFE CYCLE INPUTS:	DATA NEEDS:
Materials ▪ PE body 38 g ▪ PP cap 5 g	Energy used to extract usable raw material
Manufacture ▪ PE body: moulded ▪ PP cap: moulded	Processing energies (moulding, casting etc)
Use ▪ Refrigeration 5 days ▪ Transport 200 km	Power consumption Usage time Transport energies
Disposal ▪ Transport 100 km ▪ Recycle fraction	Transport energies Recycling process energies % economically recyclable

Eco-data in Cambridge Engineering Selector (CES)

Example material data: Polyethylene (PE)

Eco-properties: material production

Embodied energy	77 - 85 MJ/kg
Carbon dioxide	1.9 - 2.2 kg/kg
Recycle ?	✓

Eco-properties: manufacture

Injection / blow moulding	12 - 15 MJ/kg
Polymer extrusion	3 - 5 MJ/kg

Environmental notes. PE is FDA compliant - it is so non-toxic that it can be embedded in the human body (heart valves, hip-joint cups, artificial artery).

Example transport/use data:

Transport, MJ / tonne.km

Sea freight	0.11
Barge (river)	0.83
Rail freight	0.86
Truck	0.9 – 1.5
Air freight	8.3 – 15

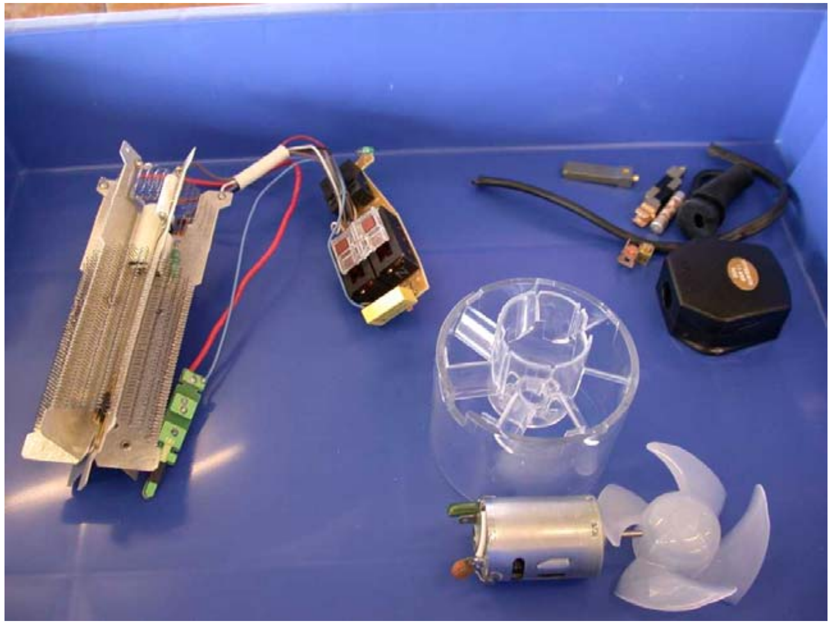
Refrigeration, MJ / m^3.day

Refrigeration (4°C)	10.5
Freezing (-5°C)	13.0

LCA using CES data: Example

Small energy-using product (EuP): Hairdryer

Hairdryer sub-systems



Materials and manufacture

ABS	Injection moulded	180 g
Nylon	Injection moulded	80 g
PVC	Moulded	13 g
Copper	Drawn	20 g
Iron	Rolled	40 g
Nichrome	Drawn	7 g
Alnico	PM methods	22 g
Muscovite	Pressed	18 g

Transport

10,000 km, sea or air

Power

Heater	1.7 kW
Fan	0.15 kW

Duty cycle

5 mins per day, 300 days/year, 3 years

LCA using CES data: Example

Enter:

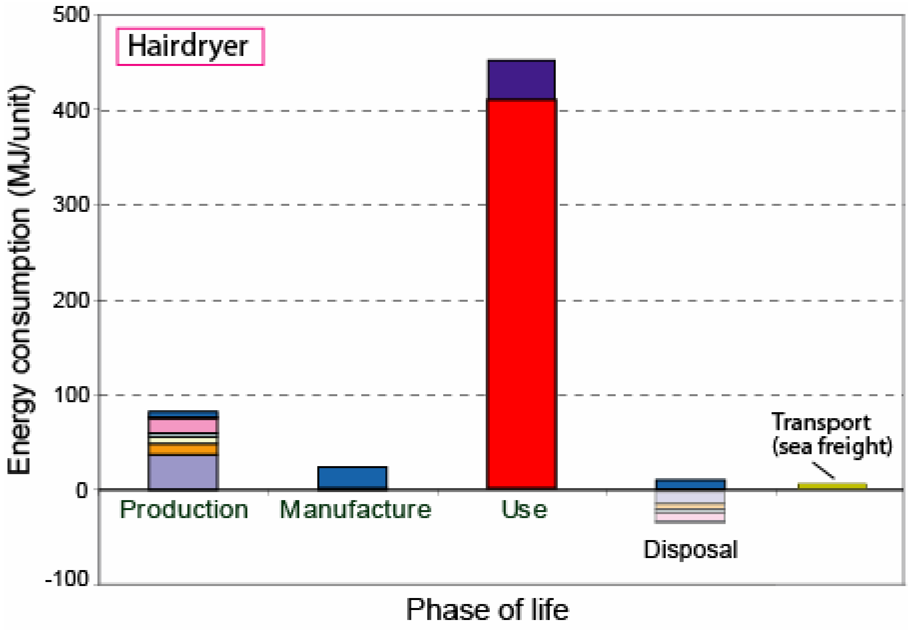
- Materials and approximate masses
- Power and duty cycle
- Transport distance and mode
- Other energy requirements

Retrieve from database:

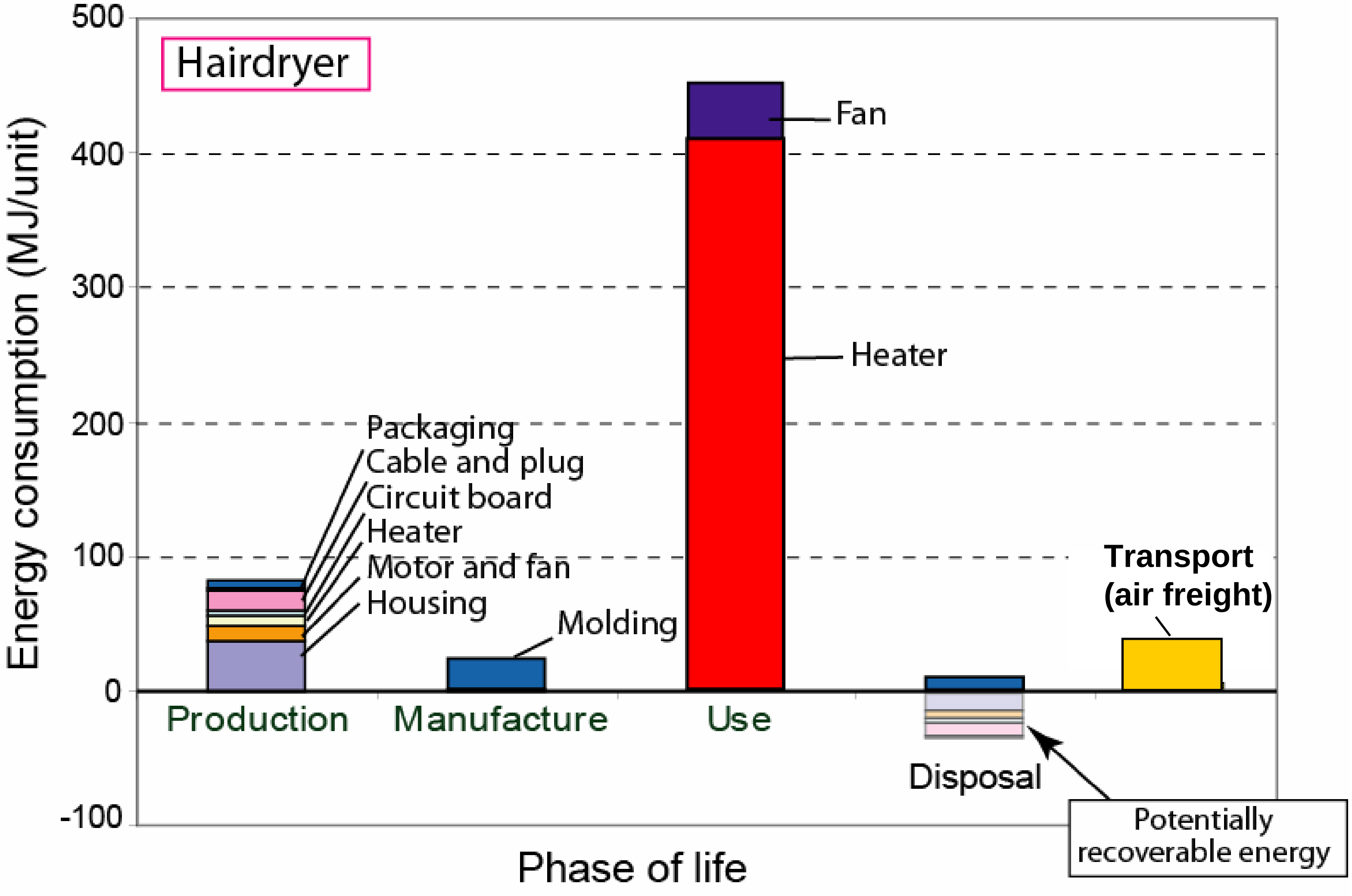
- Embodied energy of materials / kg
- Energy for manufacture / kg

Unit transport (other) energies

- Sea freight, MJ / tonne . km
- Air freight , MJ / tonne . km
- etc



Energy breakdown for hairdryer



Method is approximate but revealing - and begins to meet needs of EU directive

Application to *energy-producing* systems

- Wind turbines etc. are products: subject to ISO and national standards
  e.g. new turbines in Sweden require "EPDs" (environmental product declarations)

- Note that for wind turbine LCA:
  - Same life phases apply
  - Use phase primarily gives energy *output*
  - Use still involves some energy consumption (e.g. for maintenance)

- LCA also provides a basis for estimating the ***energy payback period***

Energy payback period:
The time taken for an energy-producing system to deliver the energy that will be consumed by the system in its entire life cycle (including disposal).

Application to wind turbines

Example LCA: Vestas V80 2.0MW onshore wind turbine

(Tjæreborg, Denmark:
80 turbine wind farm)

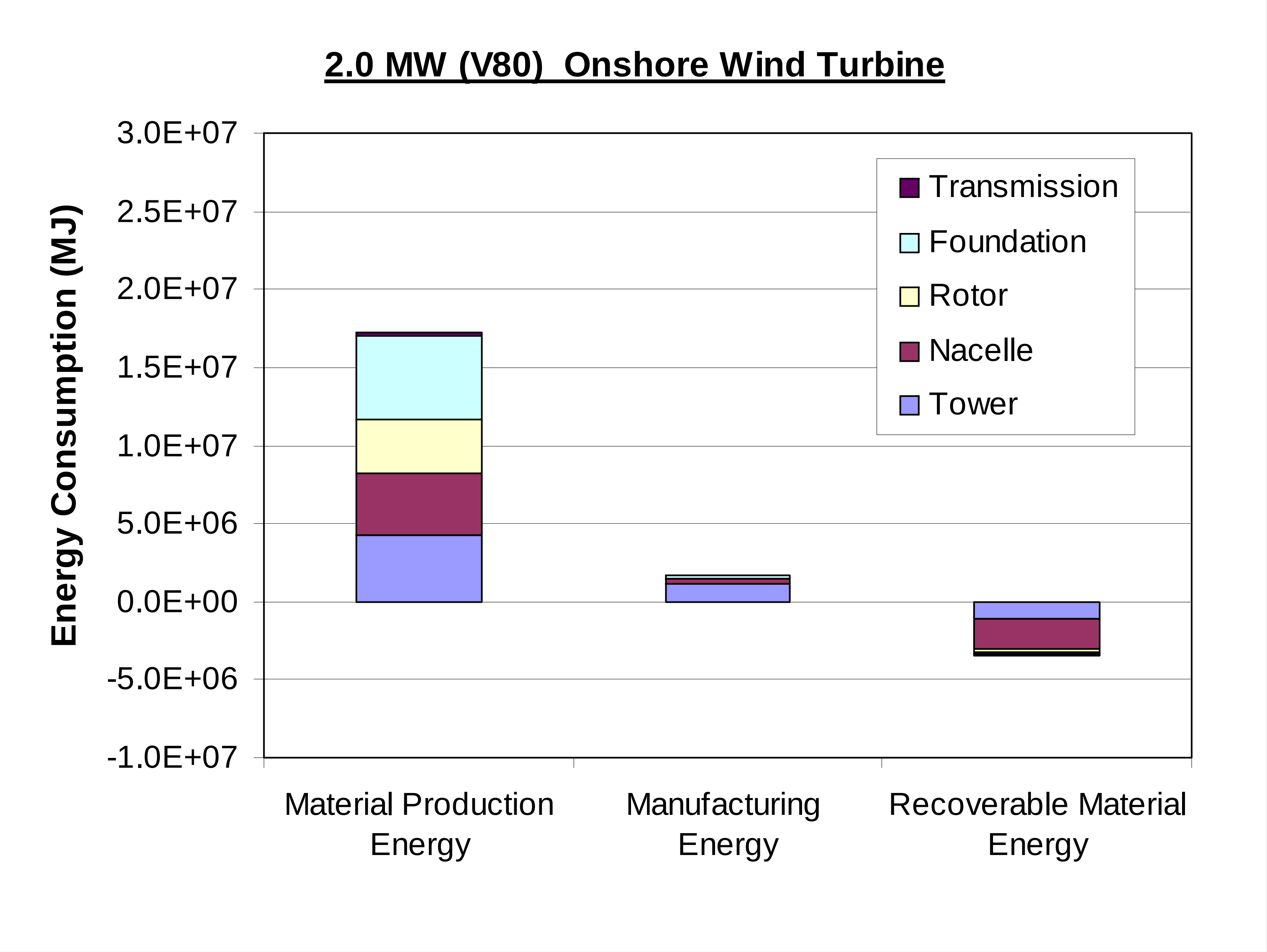
System data:
(mostly from published literature; some estimates)

Note:

- Tower, nacelle, rotor, foundation: per turbine
- Transmission: 1/80th share of sub-system for wind farm

Subsystems	Parts	Materials	Mass (tonnes)
Tower		Zn	0,20
		Steel	164
Nacelle	Gears	Stainless Steel	10
		Steel	10
	Generator	Steel	5
		Cu	5
	Transformer	Al	2
		Steel	6
		Cu	2
	Nacelle Cover	GFRP	4
	Main Shaft	Cast Iron	12
	Others	Cast Iron	4
		Stainless Steel	3
Rotor	Blades (3)	GFRP	21.5
		Cast Iron	3
	Spinner	Cast Iron	2
		GFRP	2
Foundation		Reinforced Concrete	805
		Steel	27
Transmission	Cables	Cu	0.25
		Al	0.07
	Insulators	Polyethylene	1.4

Application to wind turbines



Application to wind turbines

Example LCA: Vestas V80 2.0MW onshore wind turbine

Accuracy?

- CES energy data typically ± 20% relative to the mean
- Some uncertainty/estimation in component masses

Observations:

- Material production energy dominant (10x greater than manufacturing energy)
- Tower, nacelle, rotor, foundation: all make significant contributions
- Transmission: negligible in this case
- Dominant materials in each subsystem (in terms of production energy):
  Tower: Steel
  Nacelle: Stainless steel, Cast iron, GFRP
  Rotor: GFRP
  Foundation: Reinforced concrete
- Most recoverable material: ferrous alloys in tower and nacelle
  (cannot recycle concrete or GFRP)

Application to wind turbines

Example LCA: Vestas V80 2.0MW onshore wind turbine

Notes:

- "Recoverable Material Energy" combines estimated recycled fractions with embodied energy/kg of raw material, minus recycling processing energy

- No "manufacturing energy" included for the concrete (dominated by transport costs) or for GFRP (no data available).

Estimate of transport energy for concrete:

- 805 tonnes used in foundation
- say average of 100km travelled
- average energy of transport by truck = 1.54 MJ per tonne.km

Hence concrete transport energy per turbine = 0.12 x 10^6 MJ/turbine
(negligible compared to material energy = 4.6 x 10^6 MJ/turbine)

Application to wind turbines

Example LCA: Vestas V80 2.0MW onshore wind turbine

Payback period

- Average reported energy production per turbine = 5.63 GWh / year

(Note: *capacity factor* = fraction of installed potential actually produced
For the 2.0MW machine:
max. energy = 2.0 x 24 x 365 MWh / year = 17.5 GWh / year
hence capacity factor = 5.63 / 17.5 = 0.320)

- *Total life cycle energy used per turbine* =
(material production + manufacturing) – (recoverable material)
= 15.5×10^6 MJ = 4.31 GWh

- Hence *payback period* = 4.31/5.63 years = 9.2 months

(or with zero material recovery: 5.26/5.63 years = 11.2 months)

Payback period: of order only 10 months – realistic compared to the literature.

(Note the ability to put a sensible figure on payback, in spite of uncertainty.)

Favourable cost/kWh not automatically guaranteed – but a strong starting point.

Application to wind turbines

Comparison 1: 2.0MW vs 3.0MW (onshore)

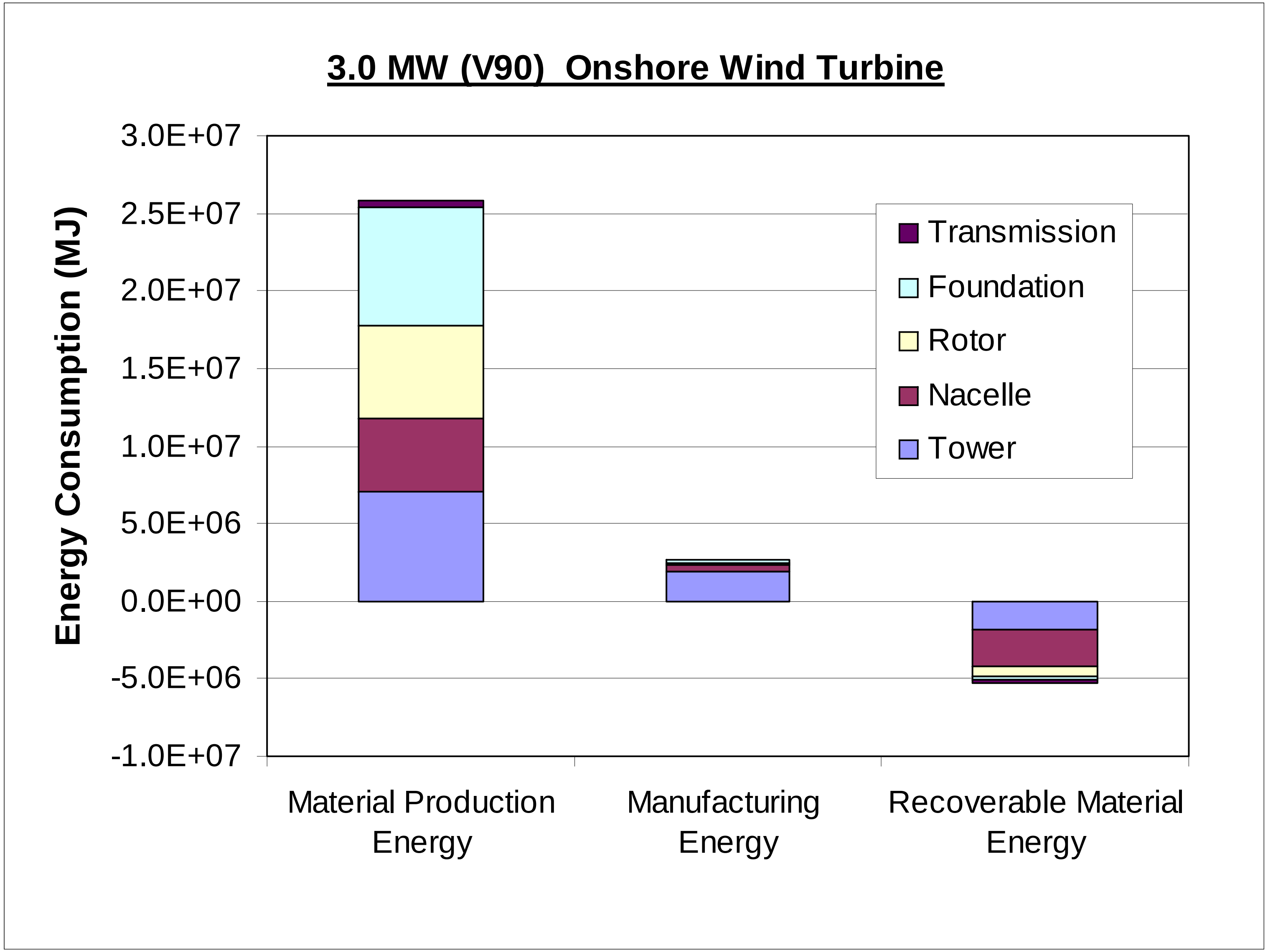
(Vestas V90 3.0MW, 100 turbine wind farm on same site)

Main differences:

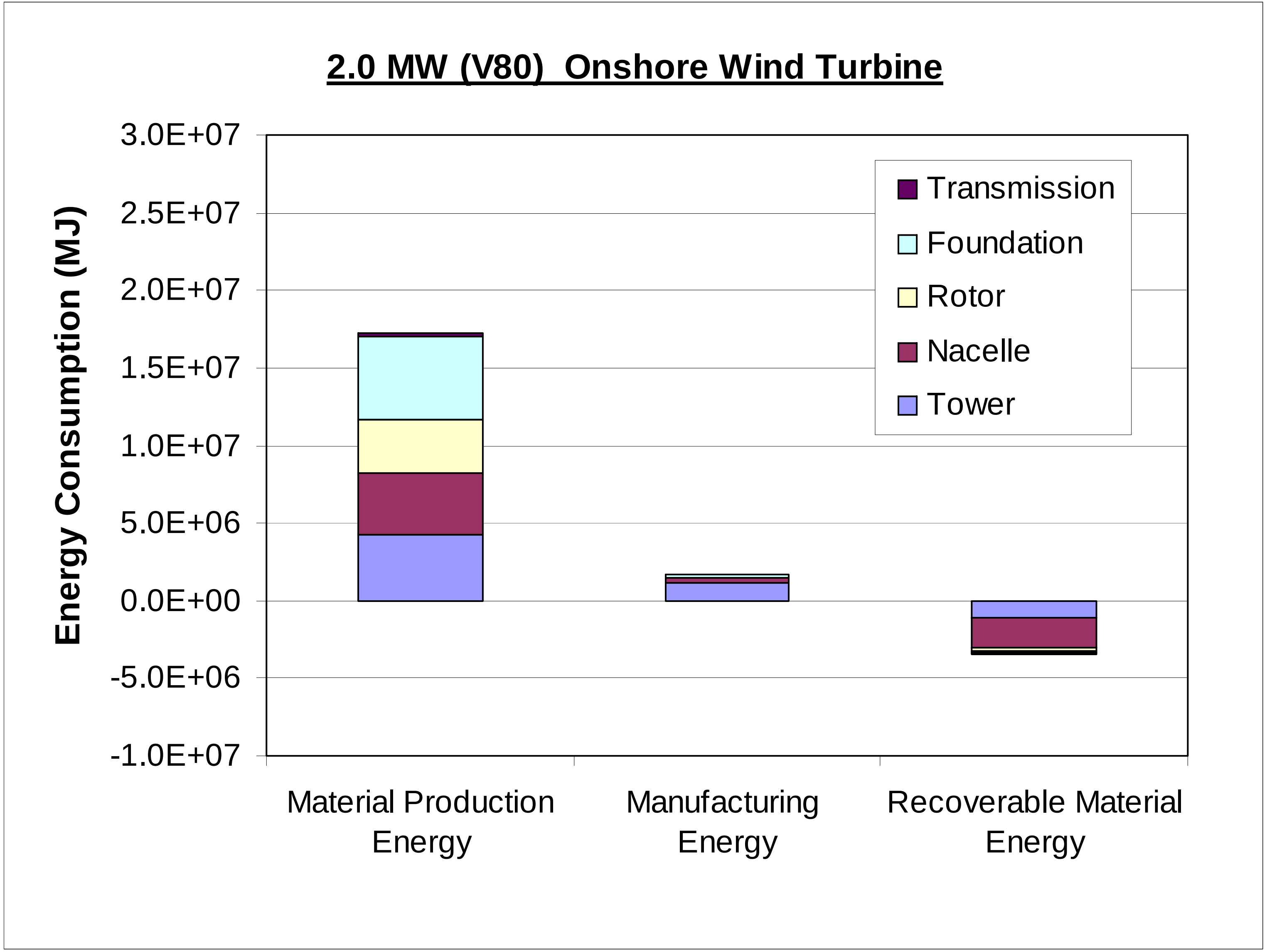
		2.0 MW		3.0 MW	
Subsystems	Parts	Materials	Mass (tonnes)	Materials	Mass (tonnes)
Tower		Steel	164	Steel	273
Rotor	Blades (3)	GFRP	21.5	CFRP	15.9
				GFRP	4.3
Foundation		Reinforced Concrete	805	Reinforced Concrete	1160
		Steel	27	Steel	36

- Taller broader tower and larger foundation required
- CFRP internal spar and GFRP skin – longer rotor blade, but lighter

Application to wind turbines



Application to wind turbines



Application to wind turbines

Comparison 1: 2.0MW vs 3.0MW (onshore)

Observations:

- Tower, rotor and foundation all greater proportions of the production energy
- But overall energy contributions scale up – almost in direct proportion to power rating

Payback period

- Average reported energy production per turbine = 7.89 GWh / year (giving a *capacity factor* = 0.30, similar to smaller machine)
- *Total life cycle energy used per turbine* = 23.3 x 10^6 MJ = 6.46 GWh
- Hence *payback period* = 6.46/7.89 years = 9.8 months

  (or with zero material recovery: 7.92/7.89 years = 12 months)

Hence: very similar payback period (slightly longer due to reduced capacity factor, and some energy-intensive materials: CFRP)

(*Note: technical advance with time means that the payback period for a given installed capacity is expected to steadily decrease*)

Application to wind turbines

Comparison 2: onshore vs. offshore (3.0MW):

(Vestas V90 3.0MW, 100 turbine wind farms:
onshore at Tjæreborg, offshore at Horns Reef, Denmark)

Application to wind turbines

Comparison 2: onshore vs. offshore (3.0MW):

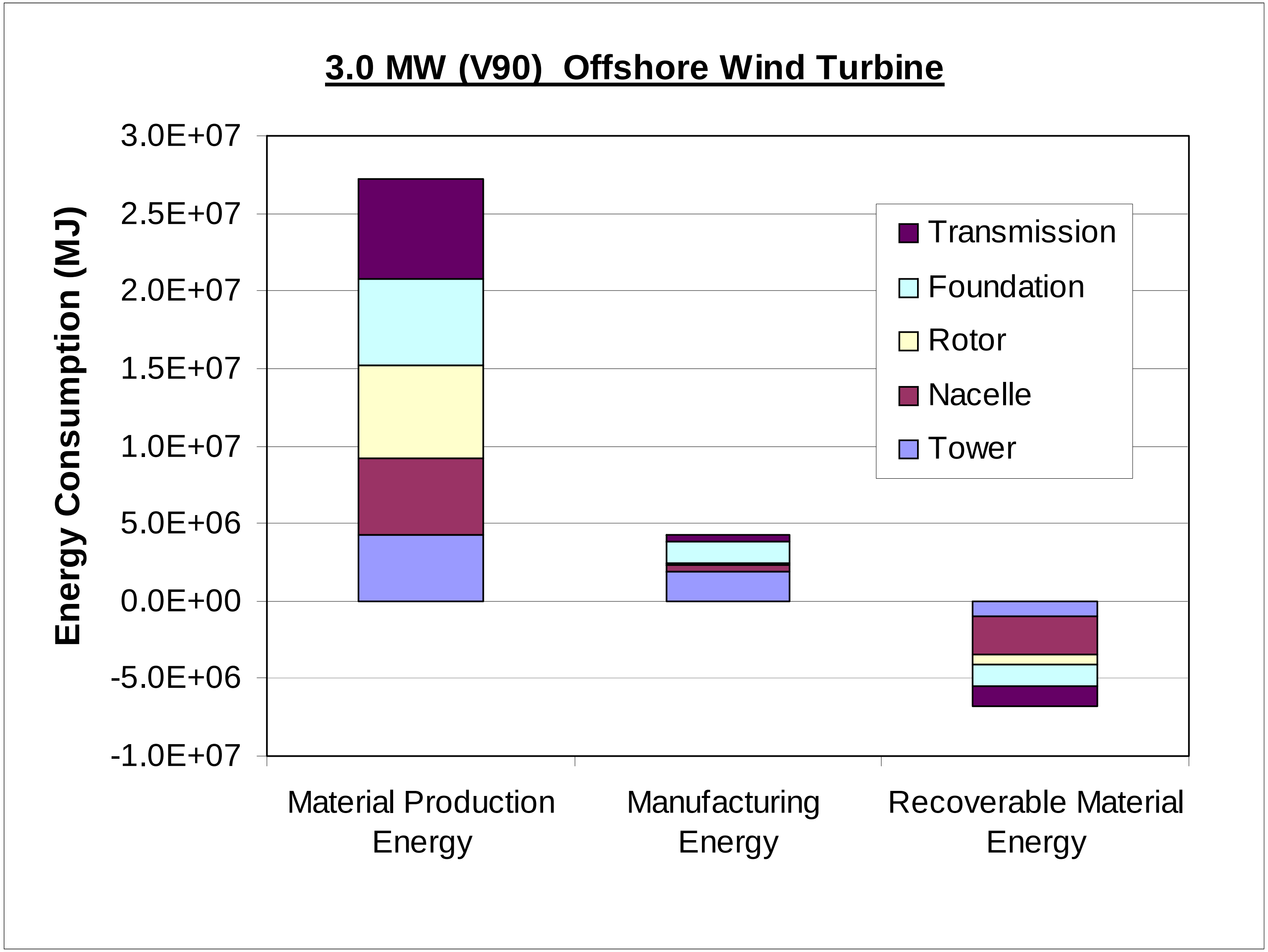
(Vestas V90 3.0MW, 100 turbine wind farms:
onshore at Tjæreborg, offshore at Horns Reef, Denmark)

Main differences:

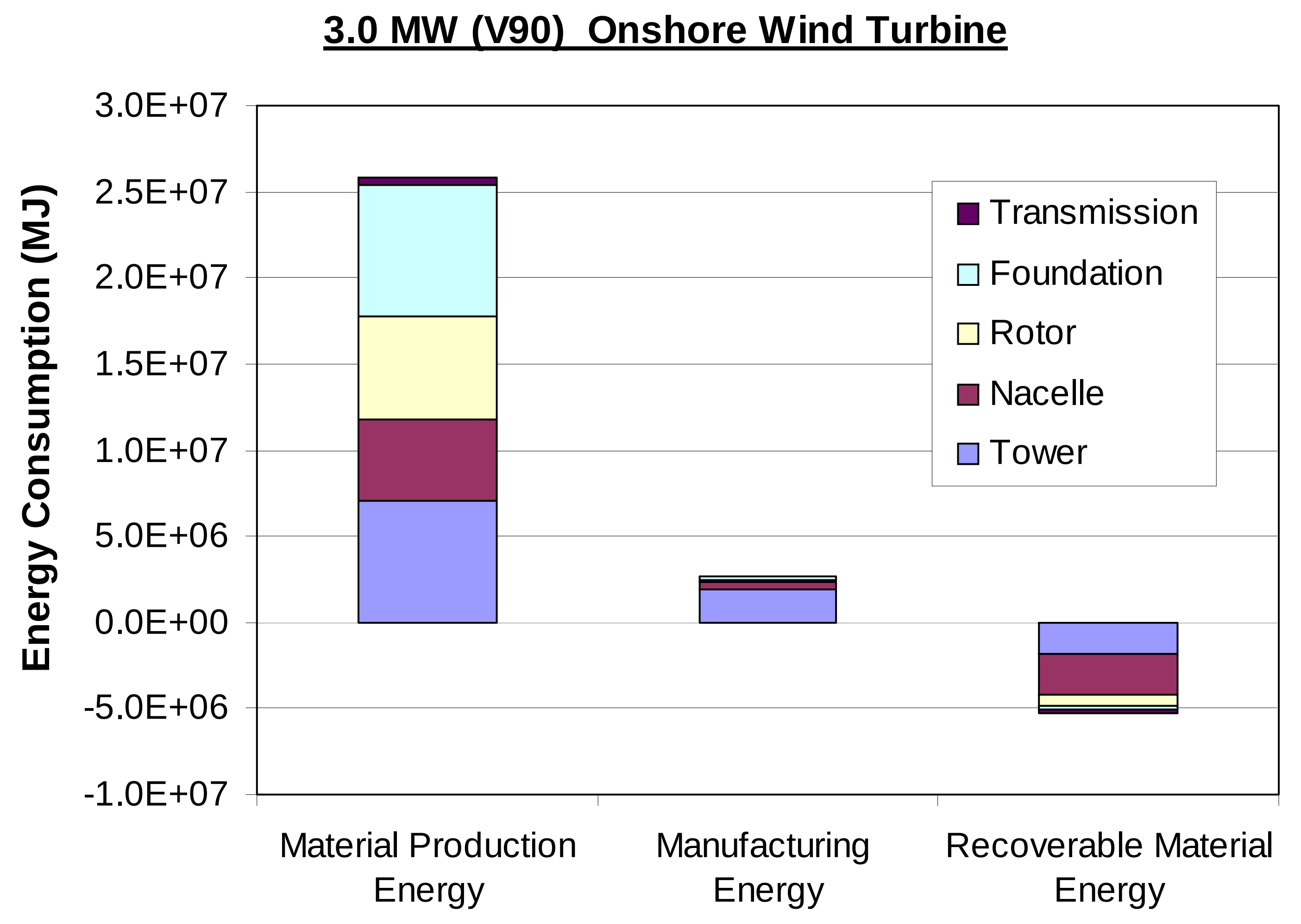
		3.0 MW onshore		3.0 MW offshore	
Subsystems	Parts	Materials	Mass (tonnes)	Materials	Mass (tonnes)
Tower		Zn	0.34	Zn	6.8
		Steel	273	Steel	150
Foundation		Reinforced Concrete	1160	Steel	197
		Steel	36	Zn	6.0
Transmission	Cabling/ transformers	Cu	0.24	Steel	19.8
		Al	0.91	Al	3.3
	Insulators/ ducting	Polyethylene	1.4	Polyethylene	4.0
				Elastomer	97
				Concrete	410

- Lightweight tower and foundation using steel, not concrete; much greater galvanic protection (Zn)
- Substantial additional cabling requirements to bring power onshore

Application to wind turbines



Application to wind turbines



Application to wind turbines

Comparison 2: onshore vs. offshore (3.0MW):

Observations:

- Transmission now a significant contributor to material energy
- Steel tower and foundation open to partial material recovery
- Overall production energy much the same

Payback period: offshore

- Average reported energy production per turbine = 14.2 GWh / year (giving a *capacity factor* = 0.54, much higher than onshore)
- *Total life cycle energy used per turbine* = 24.6×10^6 MJ = 6.84 GWh
- Hence *payback period* = 6.84/14.2 years = 5.8 months

  (or with zero material recovery: 8.73/14.2 years = 7.4 months)

Hence: much shorter payback period offshore – similar life cycle energy, but much higher capacity factor

Summary

Life Cycle Analysis

- detailed environmental impact evaluation for different life-phases:
  Material Production
  Manufacture
  Product Use + Transport
  Disposal/Recycling

Simplified LCA using Cambridge Engineering Selector

- quick, approximate LCA concentrating on *energy burden of products*

Application to renewable energy systems

- method allows realistic estimation of **payback period**:
  the time for the system to generate the energy used in its life cycle
- payback period fairly insensitive to installation size (for 2-3 MW – the picture may differ for the new 5 MW machines, or for small-scale multi-kW turbines)
- offshore installations recover energy costs more rapidly – mainly due to higher capacity factor
- typical payback periods (for large machines) only 6-12 months:
  this is not the barrier to development

Current/Future Developments

CES eco-audit for LCA

- now includes greater breakdown of *disposal* stage:
  landfill, recycle, combustion for power production

Application to renewable energy systems

- application to full size range of wind turbines:
  - how does payback period work out for small-scale wind (such as Iskra 5kW)?

- explore new designs, e.g. bamboo rotors for large-scale use in China ?
- application to other renewable energy systems (e.g. Pelamis wave power):
  but getting data from manufacturers is a problem

- all energies (material, manufacturing etc) contribute to life cycle *cost*:
  what else is needed to give realistic estimates of cost/kWh ?

Prototype Pelamis Wave Power Machine

Paper 8: Mechanical Engineering Elective

Renewable Energy Systems

Wind, Tidal and Wave Power in the UK

Additional background notes assembled from presentations courtesy of:
Clare Rhodes James (Mott-McDonald) – Wind Power
Matthew Rea (Edinburgh Designs Ltd) – Wave and Tidal Power

For further details and illustrations of wind, wave and tidal technologies, see the original Powerpoint presentations on Hugh Hunt's Website

Michael Sutcliffe, Hugh Shercliff and Mike Ashby
CUED/Granta Design

UK Renewable Energy Capacities and Costs

Total committed in 2004 (in operation, or under construction): approx. 3GW (wind 2.2GW, and 70% in Scotland)

1,428 MW Onshore Wind, 740 MW Offshore Wind (+ further 2000 MW approved, 9000 MW in planning)

118 MW Biomass, 736 MW Landfill gas, 1.3 MW Photovoltaic, 28 MW Hydro

	p/kWh current	p/kWh expected
Onshore wind	2.5-3.0	1.5-2.0
Offshore wind	5-6	2.0-3.0
Energy crops	8	
Photovoltaic	70	
Wave and tidal	n/a	4-8
Nuclear	6	3-4
Coal	3-3.5	

Ref: PIU, The Energy Report, 2002

Wind: Advantages/Disadvantages-Challenges

Advantages:

Large potential global resource, with very low carbon emissions

Reliable, established technology, with low capital costs and fast construction

Low operating and maintenance cost, and some recycling potential

Easy to decommission, with low long-term impact on site after decommissioning

Advantages offshore vs. onshore:
larger machines (3-5 MW, higher wind speeds, more continuous supply)

Disadvantages/Challenges:

Intermittency (and unpredictability) of supply – hence need for backup conventional supply (though emissions are obviously reduced when backup NOT in use)

Grid connection and compatibility

Manufacturing capacity for towers (steel) and rotors (GFRP, CFRP) outstripping supply

Variable public acceptance: visual impact, noise, proximity to (or siting on) “wild land”, impact on bird and other wildlife (all generally better offshore)

Offshore: accessibility difficult in rough seas
(e.g. for Horns Rev, Denmark: 30% of the year by sea, 90% by helicopter)

Tidal: Technologies

Alternative technologies:
- tidal stream turbines
- tidal barrages and tidal lagoons

Tidal stream turbines:
- lower flow-rate but much higher density than wind
- operating principle very similar to “underwater wind turbine” (e.g. tapered, pitched multiple blades generate torque by decelerating flow through control volume)
- prototype machines around 150-300kW

Tidal barrages: large-scale and long-established (e.g. La Rance, France, 1967: 240MW; potential of Severn estuary: 8.5 GW)

Tidal lagoons: prototype in Swansea Bay, 60MW from 5km^2

Tidal: Advantages/Disadvantages

***Advantages*:**

Predictable, but cyclic with 2 tides every 24hrs 50mins, and with monthly amplitude cycle superimposed

Potential for cost-effective power (e.g. estimated at 4-6p/kWh)

***Disadvantages*:**

Cyclic sources require alternative sources to smooth supply, but less intermittent than wind

Negative environmental impacts:
  - barrages: silting of estuary
  - tidal stream turbines: sea-bed scouring, impacts on fishing/shipping

Hostile marine environment (electrical isolation, power delivery onshore, access, maintenance)

Wave: Technologies

Alternative technologies:
  - "Salter's Duck": oscillating, floating system
  - near-shore and shoreline devices:
    e.g. oscillating enclosed water column, driving air through turbine)
  - tapered water channel (shoreline, or floating offshore):
    e.g. "Tapchan": waves amplified by channel to overtop breakwater and run back through conventional hydro-electric turbine
  - Pelamis: articulated floating pontoons

Salter's Duck has long history but ultimately unsuccessful

Prototype oscillating water column systems: 75kW-2MW, mixed success

350kW Tapchan system operating in Norway since 1985

Pelamis: 750kW prototype tested; 2MW installations in Scotland and Portugal during 2007.

Wave: Advantages/Disadvantages

Advantages**:**

Generating equipment above water-line or onshore: easier maintenance than tidal-stream systems

Relatively straightforward established technology; but likely cost/kWh after scale-up not yet known

Disadvantages**:**

Wave power density around UK approx. 0.1-1 kW/m^2, hence require relatively large area: e.g. 120m long Pelamis generates 750kW

Intermittency and unpredictability of supply, with need for backup conventional supply: this problem varies in severity depending on type of wave technology used (e.g. Tapchan stores water behind breakwater, giving smooth power output)

Generally less disturbance of marine life than tidal, but offshore installations affect fishing and shipping