1 Economics

- In assessing changes in the design of a wind turbine, it is important to evaluate that the impact such changes would have on the system cost.
- This includes:
  1. the initial capital (IC) cost
  2. balance of station (BOS) cost
  3. operation and maintenance (O&M) cost
  4. levelized replacement (LR) cost
  5. annual energy production (AEP) revenue which balances these costs
- "levelized" means to limit the impact of financial factors such as the cost of capital so that the **true impact of technical changes** can be assessed
- **Many of these costs are linked**

- The **levelized cost of electricity (COE)** has been used to **evaluate the total system impact** of any change in wind turbine designs
- The DOE and NREL have compiled statistics on a range of wind turbine rated power levels in order to develop scaling relationships
- The results lead to costs are in 2002 dollars that can be brought to present dollars using the Consumer Price Index

1.1 Cost of Energy, COE

- The cost of energy, COE, is determined using the following formula

$$COE = \frac{(FCR)(ICC)}{AEP_{net}} + AOE \tag{1}$$

where

$$\begin{aligned}
COE &= \text{levelized cost of energy [\$/kW-h]} && (2)\\
FCR &= \text{fixed charge rate [1/yr]} && (3)\\
ICC &= \text{initial capital cost [\$]} && (4)\\
AEP_{net} &= \text{net annual energy production [kW-h/yr]} && (5)\\
AOE &= \text{annual operating expenses} && (6)\\
&= LLC + \frac{O\&M + LRC}{AEP_{net}} && (7)\\
LLC &= \text{land lease cost} && (8)\\
O\&M &= \text{levelized O\&M cost} && (9)\\
LRC &= \text{levelized replacement/overhaul cost.} && (10)
\end{aligned}$$

- FCR is the annual amount per dollar, of **initial capital cost** needed to cover the capital cost, a return on debt and equity, and various other fixed charges including
  1. construction financing
  2. financing fees
  3. return on debt and equity
  4. depreciation
  5. income and property taxes
  6. insurance

- The FCR is set as 0.1158 per year.

- ICC is the sum of costs of the wind turbine system and the balance of station, BOS, cost that include
  1. wind turbine rotor including
     (a) rotor blades
     (b) rotor hub
     (c) pitch mechanism and bearings
     (d) spinner, nose cone
  2. drive train, nacelle including
     (a) low-speed shaft
     (b) bearings
     (c) gearbox
     (d) mechanical break, high-speed coupling, associated components
     (e) generator
     (f) variable-speed electronics
     (g) yaw drive and bearing
     (h) main frame
     (i) electrical connections
     (j) hydraulic and cooling systems
     (k) nacelle cover
  3. control, safety system and conditioning monitoring
  4. tower
  5. balance of station, including
     (a) foundation/support structure
     (b) transportation

(c) roads, civil work
(d) assembly and installation
(e) electrical interface/connections
(f) engineering permits

- *ICC* **for off-shore wind turbines** also includes
  1. marinization, to handle the marine environment
  2. port and staging equipment
  3. personal access equipment
  4. scour protection
  5. security bond to cover decommissioning
  6. offshore warranty premium

- **Annual operating expenses (*AOE*)** includes
  1. land or ocean bottom lease cost
  2. levelized $O\&M$ cost
  3. levelized replacement/overhaul cost (LRC)
- **O&M costs** in [$/kW-h] are the largest portion of the AOE, it includes:
  1. labor, parts, and supplies for scheduled turbine maintenance
  2. labor, parts, and supplies for unscheduled turbine maintenance
  3. parts and supplies for equipment and facilities maintenance
  4. labor for administration and support
- **Levelized replacement/overhaul cost (*LRC*)** in [$/kW] is the cost of major replacements and overhauls over the life of the wind turbine
- ***net* annual energy production (*AEP*)** is the **projected energy output of the turbine based on a given annual average wind speed**
- ***Gross*** AEP is adjusted for factors such as:
  1. rotor coefficient of power
  2. mechanical and electrical conversion losses
  3. blade "soiling" losses
  4. wind farm array losses
  5. machine availability

1.2 Component Estimate Formulas

- **Rotor Blade Mass.** A direct correlation between the mass (weight) of wind turbine rotor and its radius ($m \propto R^3$)

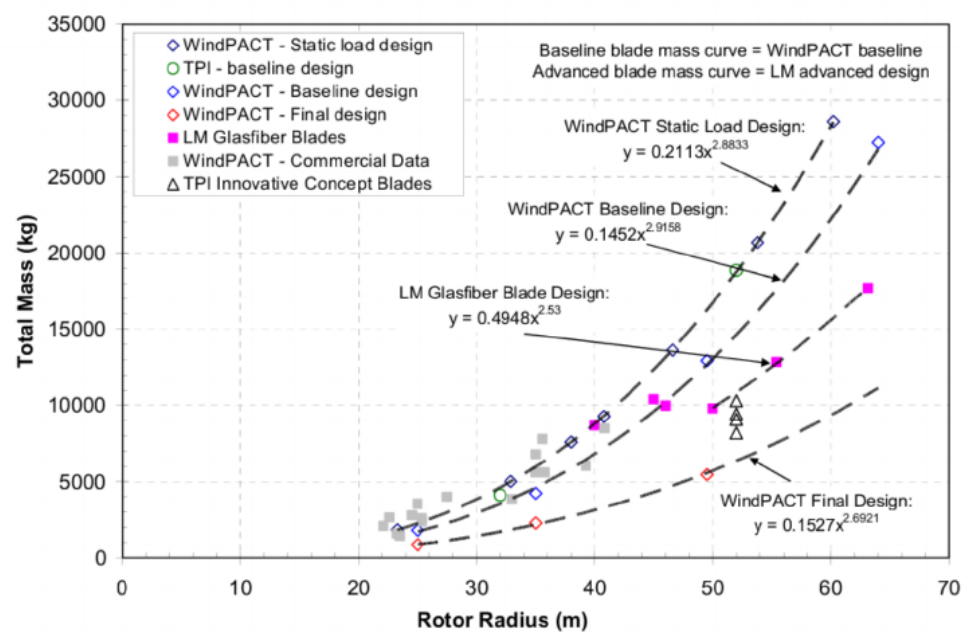

Figure 1: Wind turbine rotor blade mass correlation with rotor radius.

- For the baseline rotor design

$$m = 0.1452R^{2.9156} \tag{11}$$

- With advanced (fiberglass) materials

$$m = 0.4948R^{2.53}. \tag{12}$$

- **Rotor Blade Cost.** The increased mass of the rotor that comes with increasing the rotor radius translates into an increase in the cost of the rotor
- These costs include:
    1. material
    2. tooling
    3. labor
    4. overhead
    5. profit

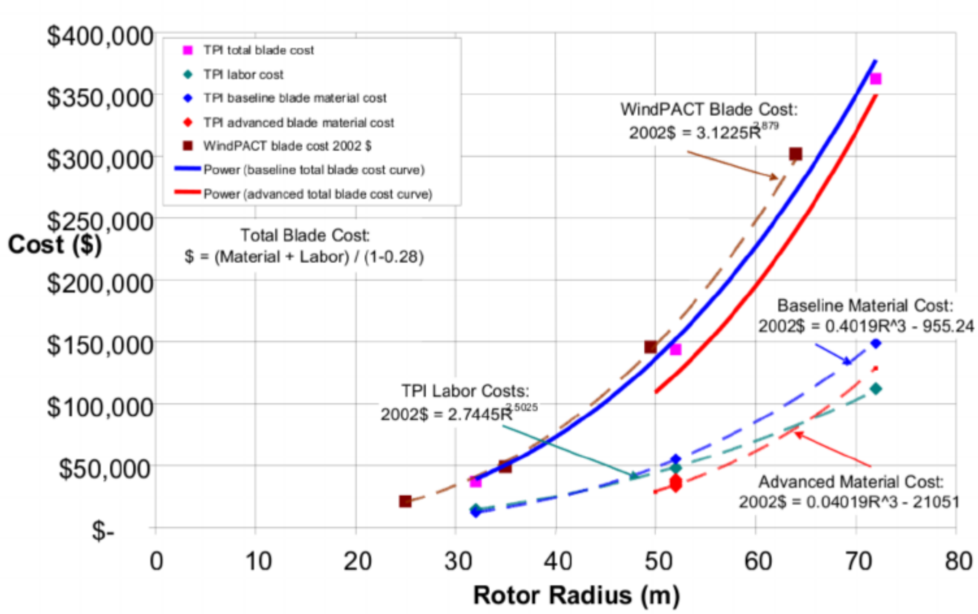

Figure 2: Wind turbine rotor blade cost, labor cost, and baseline and advanced material cost correlations with rotor radius.

$$\text{Baseline Rotor Cost} = 3.1225R^{2.879} \tag{13}$$

$$\text{Baseline Material Cost} = 0.4019R^3 - 955.24. \tag{14}$$

$$\text{Labor Cost} = 2.7445R^{2.5025}. \tag{15}$$

$$\text{Advanced Material Cost} = 0.04019R^3 - 21051. \tag{16}$$

- **Rotor Hub Cost.** Expected to scale approximately linearly with the mass of the rotor

$$\text{Hub Mass} = 0.954(\text{Single Blade Mass}) + 5680.3 \tag{17}$$

$$\text{Hub Cost} = \text{Hub Mass} + 5680.3 \tag{18}$$

- **Pitch Mechanism and Bearings Cost.** The mass scales linearly with the total (three) blade mass as

$$\text{Total Pitch Bearing Mass} = 0.1295(\text{Total (3) Blade Mass}) + 491.31. \tag{19}$$

$$\text{Total Pitch Mechanism Mass} = 1.328(\text{Total Pitch Bearing Mass}) + 555. \tag{20}$$

$$\text{Total Pitch System Cost} = 0.4801 D^{2.6578}. \tag{21}$$

- **Spinner Nose Cone Cost.** The spinner nose cone fits over the rotor hub to provide an aerodynamic profile

$$\text{Nose Cone Mass} = 18.5D - 520.5 \tag{22}$$

$$\text{Nose Cone Cost} = 5.57(\text{Nose Cone Mass}) \tag{23}$$

- **Low-speed Shaft Cost.** The rotor hub attaches to the low-speed shaft and transmits the rotor torque to the gear box.

$$\text{Low-speed Shaft Mass} = 0.0142D^{2.888} \tag{24}$$

$$\text{Low-speed Shaft Cost} = 0.0100D^{2.887} \tag{25}$$

- **Main Bearings Cost.** The low-speed shaft rotates on a set of main bearings
- The forces on the bearings are directly related to the weight and aerodynamic loading of the rotor, which should scale with the rotor disk diameter

$$\text{Main Bearing Mass} = (0.000123D - 0.000123)D^{2.5} \tag{26}$$

$$\text{Main Bearing Cost} = 35.2(\text{Main Bearing Mass}) \tag{27}$$

- **Gearbox Cost.** The input to the gearbox comes from the aerodynamic torque transmitted through the low-speed shaft

  1. Three-stage Planetary/Helical Gearbox

$$\text{Mass} = 70.94(\text{Low-speed Shaft Torque})^{0.759} \tag{28}$$

$$\text{Cost} = 16.45(\text{Rated Power})^{1.249} \tag{29}$$

  2. Medium-speed Single-stage Drive

$$\text{Mass} = 88.29(\text{Low-speed Shaft Torque})^{0.774} \tag{30}$$

$$\text{Cost} = 74.10(\text{Rated Power}) \tag{31}$$

  3. Multi-path Drive

$$\text{Mass} = 139.69(\text{Low-speed Shaft Torque})^{0.774} \tag{32}$$

$$\text{Cost} = 15.26(\text{Rated Power})^{1.249} \tag{33}$$

- **Mechanical Brake/High-speed Coupling Cost.** Intended to prevent rotor rotation when the wind speed exceeds the cut-out velocity
- The brake needs to overcome the aerodynamic torque produced by the rotor disk, and therefore its mass and cost should scale with the torque or power

$$\text{Brake/Coupling Cost} = 1.9894(\text{Rated Power}) - 0.1141 \quad (34)$$

$$\text{Brake/Coupling Mass} = 0.1(\text{Brake/Coupling Cost}) \quad (35)$$

- **Electric Generator Cost.** Like the gearbox, there are three configurations, along with direct drive

  1. High-speed Generator with Three-stage Planetary/Helical Gearbox

  $$\text{Mass} = 6.47(\text{Rated Power})^{0.9223} \tag{36}$$

  $$\text{Cost} = 65.00(\text{Rated Power}) \tag{37}$$

  2. Medium-speed Permanent Magnet Generator with Single-stage Drive

  $$\text{Mass} = 10.51(\text{Rated Power})^{0.9223} \tag{38}$$

  $$\text{Cost} = 54.73(\text{Rated Power}) \tag{39}$$

  3. Permanent Magnet Generators with Multi-path Drive

  $$\text{Mass} = 5.34(\text{Rated Power})^{0.9223} \tag{40}$$

  $$\text{Cost} = 48.03(\text{Rated Power}) \tag{41}$$

  4. Permanent Magnet Generator with Direct Drive

  $$\text{Mass} = 661.25(\text{Low-speed Shaft Torque})^{0.6060} \tag{42}$$

  $$\text{Cost} = 219.33(\text{Rated Power}) \tag{43}$$

- **Variable-speed Electronics Cost.** Consists of a power converter that can manage the power level under variable speed operation. The converters are designed based on the rated power

$$\text{Cost} = 79.0(\text{Rated Power}) \tag{44}$$

- **Yaw Drive and Bearing Cost.** Rotates the rotor disk plane to be perpendicular to the wind direction
- The yaw bearing supports the full weight of the rotor and all of the components in the nacelle, which scale with the rotor diameter, D.

$$\text{Mass} = 0.00144D^{3.314} \tag{45}$$

$$\text{Cost} = 0.0678D^{2.964} \tag{46}$$

- **Mainframe Cost.** The internal structure inside of the nacelle that supports the main bearings, gearbox and generator
- The mass an cost is then broken down into the four arrangements presented with the electric generator

1. High-speed Generator with Three-stage Planetary/Helical Gearbox

$$\text{Mass} = 2.233D^{1.953} \tag{47}$$

$$\text{Cost} = 9.489D^{1.953} \tag{48}$$

2. Medium-speed Permanent Magnet Generator with Single-stage Drive

$$\text{Mass} = 1.295D^{1.953} \tag{49}$$

$$\text{Cost} = 303.96D^{1.067} \tag{50}$$

3. Permanent Magnet Generators with Multi-path Drive

$$\text{Mass} = 1.721D^{1.953} \tag{51}$$

$$\text{Cost} = 17.92D^{1.672} \tag{52}$$

4. Permanent Magnet Generator with Direct Drive

$$\text{Mass} = 1.228D^{1.953} \tag{53}$$

$$\text{Cost} = 627.28D^{0.850} \tag{54}$$

- Internal support structure allowance for platforms and railings to allow for safe inspections and maintenance

$$\text{Platform Mass} = 0.125(\text{Mainframe Mass}) \tag{55}$$

$$\text{Platform Cost} = 8.7(\text{Platform Mass}) \tag{56}$$

- **Electrical Connections Cost.** Including electronic switching gear, and any tower wiring. The cost estimate is \$40/kW of rated power

$$\text{Cost} = 40(\text{Rated Power}). \tag{57}$$

- **Hydraulic and Cooling Systems Cost.** Estimated to be a fixed percentage of the wind turbine rated power

$$\text{Mass} = 0.08(\text{Rated Power}) \tag{58}$$

$$\text{Cost} = 12(\text{Rated Power}) \tag{59}$$

- **Nacelle Cover Cost.** Shields the internal components of the nacelle from the weather

$$\text{Cost} = 11.537(\text{Rated Power}) + 3849.7 \tag{60}$$

$$\text{Mass} = 0.1(\text{Nacelle Cost}). \tag{61}$$

- **Control, Safety System, Condition Monitoring Cost.** Taken to be
  1. a fixed cost of \$35,000 for land-based wind turbines
  2. Estimated cost is \$55,000 for off-shore wind turbines

- **Tower Cost** Designed to withstand the compression loads of the **combined masses** it supports, as well as the bending loads produced by the **axial forces** on the rotor which scale with the rotor disk area
- The maximum bending stress scales with the rotor diamater and hub height

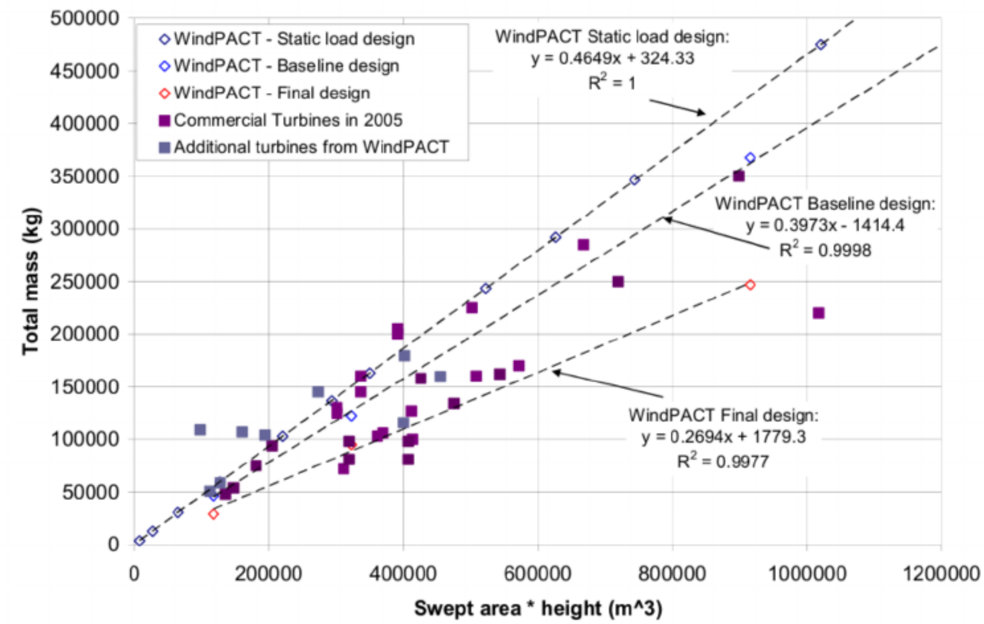

Figure 3: Wind turbine tower mass correlation with the product of the rotor area and hub height.

$$\text{Baseline Design Mass} = 0.3973(\text{Rotor Area})(\text{Hub Height}) - 1414. \tag{62}$$

$$\text{Advanced Design Mass} = 0.2694(\text{Rotor Area})(\text{Hub Height}) + 1770. \tag{63}$$

$$\text{Cost} = 1.50(\text{Mass}). \tag{64}$$

- **Transportation Cost** of the wind turbine large rotors is a considerable factor in the cost of a new wind turbine
- The rated power scales with the rotor diameter, so that the cost of transportation is estimate based on the rated power with units of \$/kW

$$\text{Transportation Cost Factor} = 1.581\times10^{-5}(\text{Rated Power})^2-0.0375(\text{Rated} \tag{65}$$

the transportation cost is

$$\text{Transportation Cost} = (\text{Transportation Cost Factor})(\text{Rated Power}). \tag{66}$$

- **Roads, Civil Work Cost** such as increasing the width of existing roads or bridges, are needed to gain access to a wind turbine location
- Estimates involve a cost factor and the rated power (\$/kW) of the wind turbine on which the size and mass of the components scale given by

$$\text{Roads, Civil Work Cost Factor} = 2.17\times10^{-6}(\text{Rated Power})^2-0.0145(\text{Rate} \tag{67}$$

and

$$\text{Roads, Civil Work Cost} = (\text{Roads, Civil Work Cost Factor})(\text{Rated Power}) \tag{68}$$

- **Assembly and Installation Cost** two most important wind turbine design parameters are hub height and rotor diameter

- The cost in 2002 dollars is given as

$$\text{Cost} = 1.965[(\text{Hub Height})(\text{Rotor Diameter})]^{1.1736}. \tag{69}$$

- **Electrical Interface/Connections Cost** covers the turbine transformer and the individual share of cables from the wind turbine to the substation

- Based on historic data, the cost estimate in 2002 dollars, is

$$\text{Cost} = (\text{Electrical Interface/Connections Cost Factor})(\text{Rated Power}) \tag{70}$$

where

$$\text{Electrical Interface/Connections Cost Factor [\$/kW]} = 3.49\times10^{-6}(\text{Rated} \tag{71}$$

- **Engineering and Permit Cost** involves the design of the entire wind energy facility and the procurement of permits needed to erect the facility

- The costs depend highly on the location, environmental conditions, availability of electrical grid access, and local permitting conditions

- The cost estimate in 2002 dollars, is given as

$$\text{Cost} = (\text{Engineering and Permit Cost Factor})(\text{Rated Power}) \tag{72}$$

where the cost factor is given as

$$\text{Engineering and Permit Cost Factor [\$/kW]} = 9.94\times10^{-4}(\text{Rated Power})+ \tag{73}$$

- **Levelized Replacement Cost** is a sinking fund factor that is intended to cover long-term replacements and overhaul of major turbine components
- The cost estimate in 2002 dollars, is

$$\text{Cost} = (\text{Levelized Replacement Cost Factor})(\text{Rated Power}) \tag{74}$$

where the cost factor is given as

$$\text{Levelized Replacement Cost Factor [\$/kW]} = 10.7(\text{Rated Power}) \tag{75}$$

- **Operations and Maintenance Cost** covers the day-to-day operations that include scheduled and unscheduled maintenance of the wind turbine(s)
- Based on historical operations of land-based wind farms, the recommended $O\&M$ costs are \$0.007/kW-h, namely

$$\text{Cost} = 0.007(\text{AEP [kW-h]}) \tag{76}$$

- **Land Lease Cost** includes lease fees for land used for wind farm development

- The factors vary widely depending on the wind class of the particular site, the nature and value of the land, and the potential market price for the wind
- An estimate of the lease costs is

$$\text{Cost} = 0.00108(\text{AEP [kW-h]}) \tag{77}$$

1.3 Example Cost Breakdown

- **Example:** Land-based 1500 kW (rated) wind turbine with a rotor diameter of 70 m. and a hub height of 65 m.

Table 1: Component cost breakdown for a land-based 1500 kW (rated) wind turbine with a rotor diameter of 70 m. and a hub height of 65 m.

Component	**Cost ($1000)**	**Mass (kg)**
Rotor	**237**	**28,291**
Blades	152	13,845
Hub	43	10,083
Pitch mechanism and bearings	38	3,588
Spinner, Nose cone	4	775
Drive train, Nacelle	**617**	**43,556**
Low-speed shaft	21	3,025
Bearings	12	679
Gearbox	153	10,241
Mech. brake, HS-coupling etc.	3	-
Generator	98	5,501
Variable spd. electronics	119	-
Yaw drive and bearing	20	1,875
Main frame	93	19,763
Electrical connections	60	-
Hydraulic, Cooling system	18	120
Nacelle cover	21	2,351
Control, Safety System, Condition Monitoring	35	-
Tower	147	97,958
Turbine Capital Cost (TCC)	**1,036**	**169,804**
Balance of Station (BOS)	**367**	-
Foundations	46	-
Transportation	50	-
Roads, Civil Work	79	-
Assembly & Installation	38	-
Electrical Interface/Connections	122	-
Engineering & Permits	32	-
Initial Capital Cost (ICC)	**1,403**	**169,804**
Installed Cost/kW	**935**	-
Turbine Capital/kW without BOS & Warranty	**691**	-
Levelized replacement cost/yr (LRC)	**16**	-
(O&M) per turbine per year	**30**	-
Land lease cost (LLC)	**5**	-
Capacity Factor	**32.8%**	
Net Annual Energy Production (AEP MW-h)	**4312**	
Fixed rate charge (FCR)	**11.85%**	
COE ($/kW-h)	**0.0496**	

- The annual cost of O&M, replacement and land lease totals \$51,000, which is approximately 3.6% of the ICC

- Wind turbine capacity factor is based on probability of winds being between V_{rated} and $V_{cut-out}$ with the net annual production (AEP) being

$$AEP = (P(V_{rated-cutout})(24)(365)(1500) = 4,312\,\text{MW-h}. \tag{78}$$

- The annual operating expenses (AOE) are then

$$AOE = LLC + \frac{O\&M + LRC}{AEP_{net}} \tag{79}$$
$$= \frac{\$5000}{4312000_{\text{kW-h}}} + \frac{\$30000+\$16,000}{4312000_{\text{kW-h}}} \tag{80}$$
$$= 0.011 \tag{81}$$

where all of the operating expenses have been normalized by the AEP in units of [kW-h]

- The cost of electricity (COE) is then

$$COE = \frac{(FCR)(ICC)}{AEP} + AOE \tag{82}$$
$$= \frac{0.1185)(\$1403000)}{4312000_{\text{kW-h}}} + 0.011 \tag{83}$$
$$= 0.0496 \tag{84}$$

where the fixed rate charge (FRC) is taken to be 11.85%