UPGRADED CALCULATOR FOR CO_2 PIPELINE SYSTEMS

Technical Study

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This report describes upgrade of a computer programme for calculating the cost of CCS systems sponsored by the IEA Greenhouse Gas R&D Programme. This report was prepared by:

Gastec UK, Orchard Business Centre,
Stoke Orchard, Cheltenham

and

AMEC, AMEC House, Yarm Road, Darlington, County Durham DL1 4JN, United Kingdom

The principal researchers were:

- I. Summerfield (Gastec)
- T. Dennish (Gastec)
- J. Watt (AMEC)

To ensure the quality and technical integrity of the research undertaken by the IEA Greenhouse Gas R&D Programme (IEA GHG) each study is managed by an appointed IEA GHG manager. As this work was an upgrade of an existing computer program no external review was performed.

The IEA GHG Manager for this report : Mike Haines

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Further information or copies of the report can be obtained by contacting the IEA GHG Programme at:

IEA Greenhouse R&D Programme, Orchard Business Centre, Stoke Orchard, Cheltenham Glos. GL52 7RZ. UK
Tel: +44 1242 680753 Fax: +44 1242 680758
E-mail: mail@ieaghg.org
www.ieagreen.org.uk

UPGRADED CALCULATOR FOR CO_2 PIPELINE SYSTEMS

Background

IEAGHG had a cost calculation computer program for CCS systems developed by Woodhill Engineering[1] some years ago (ref report PH4-6). This enabled high level cost estimates to be made of CO_2 capture and storage systems and was based on Excel. Within this spreadsheet was a routine for calculating the cost of CO_2 trunk lines which was found to have a sizing routine based on oversimplified pressure drop equations and averaged physical properties of CO_2. In 2006 a new model, based on another spreadsheet, was developed for sizing and costing distributed CO_2 collection networks. This was done as part of the two studies which were undertaken on distributed CO_2 capture and collection. It was felt that the CO_2 trunk line sizing routine should be improved and that at the same time the pipe network design program should be made available as part of the calculation suite.

Study approach

A contract to develop and upgrade the original Woodhill program and the network program was awarded to Gastec UK/AMEC who had already produced the new network design program. After obtaining the original code from Woodhill-Frontier options were examined and it was felt that as both programs were Excel based it would be simplest to amalgamate them into one program using the original Woodhill interface where possible. The possibility of adding a graphical map based interface for the distributed collection network was investigated as an additional option but although possible the necessary licence for commercial use was found to be too costly. It was on this basis that Gastec UK/AMEC proceeded with the development of the upgraded calculator.

Results and Discussion

The contractor developed a new pressure drop calculation procedure for CO_2 trunk lines segmenting the lines into 40 elements of equal length to account accurately for compressible flow. Calculations are based on turbulent flow with the internal pipe roughness of typical carbon steel line pipe. Tables of the physical properties of pure CO_2 (Density and viscosity) are used as the basis for the calculations. The range of valid temperatures and pressures covers from -50 to +75 °C and from 1 bara to maximum 1000bara pressure[2]. Intermediate values in the tables were obtained by interpolation. Consideration was given to allowing different CO_2 purities but this was found to seriously complicate the calculation as a full multi-component physical property routine would have to be acquired and built in. Calculations are based on isothermal conditions with no change in elevation.

[1] Now Woodhill Frontier following a take over

[2] Below 0°C max pressure 700bara and below -25°C max pressure 300bar

Other additional features over the original calculator are a greater choice of terrain types and the ability to set percentages of each type of terrain. It is also possible now to specify the count of road/rail/river crossings which are then taken into account in the cost estimate. The contractor also introduced routines to allow costs to be escalated using any of the four main published industrial construction cost indices, the possibility to calculate costs in different currencies default exchange rates which can be overidden. The ability to adjust costs for different world regions using regional cost factors was retained and extended to the other parts of the model.

Because of the intricacy of the original trunk line sizing routines which included sizing/ costing of gas and hydrogen lines the improved sizing/cost routine was added as an option leaving choice of the old less accurate routine intact so that users could still make comparisons with earlier estimates. The user can still use the system to cost complete CCS systems but with the new CO_2 pipeline sizing and costing routine.
Alternatively users can select an option to size and cost CO_2 trunk lines individually using a separate input sheet. When used in this mode graphical representations of conditions along the pipeline are displayed. The routine calculates the requirements and costs for booster compression or pumping as did the original model but also now includes metering and block valve costs as well. Pipeline costs are based on statistical data from pipeline projects collected by AMEC and are derived from lookup tables. The cost data indicate that for smaller diameter lines there is little difference in total installed cost and the table groups some diameters together. The model has been run on some typical CO2 pipelines varying diameter to change the number of pumping/compression stations needed. The results are shown graphically in fig 1 and 2.

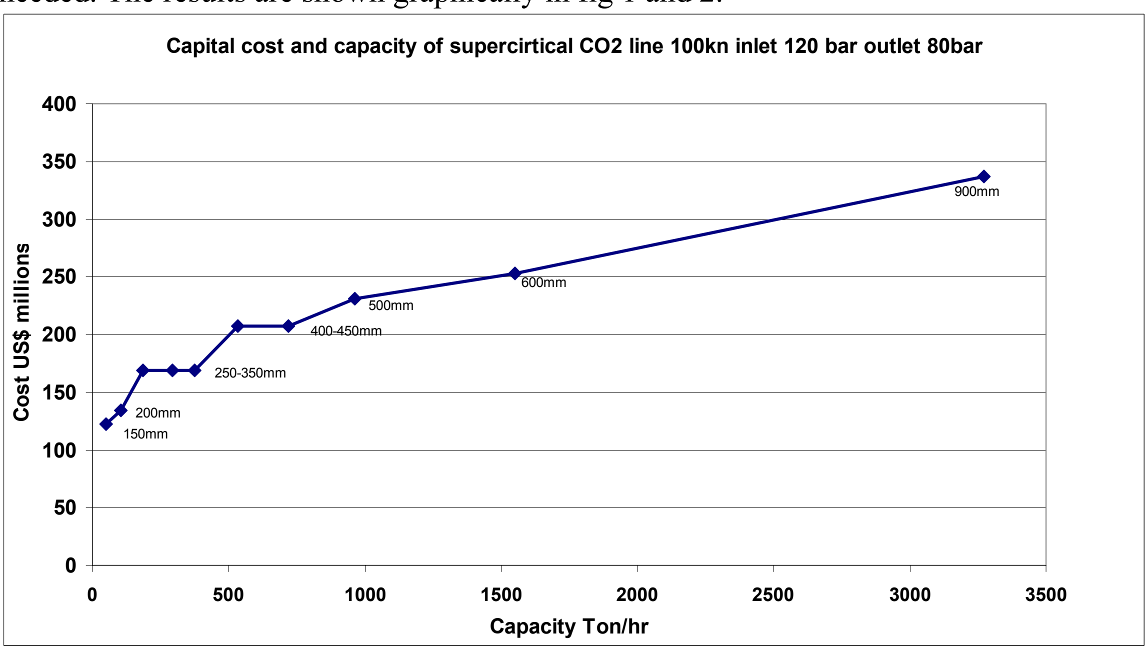

Fig 1 Capital cost v capacity for a 100km supercritical CO_2 line

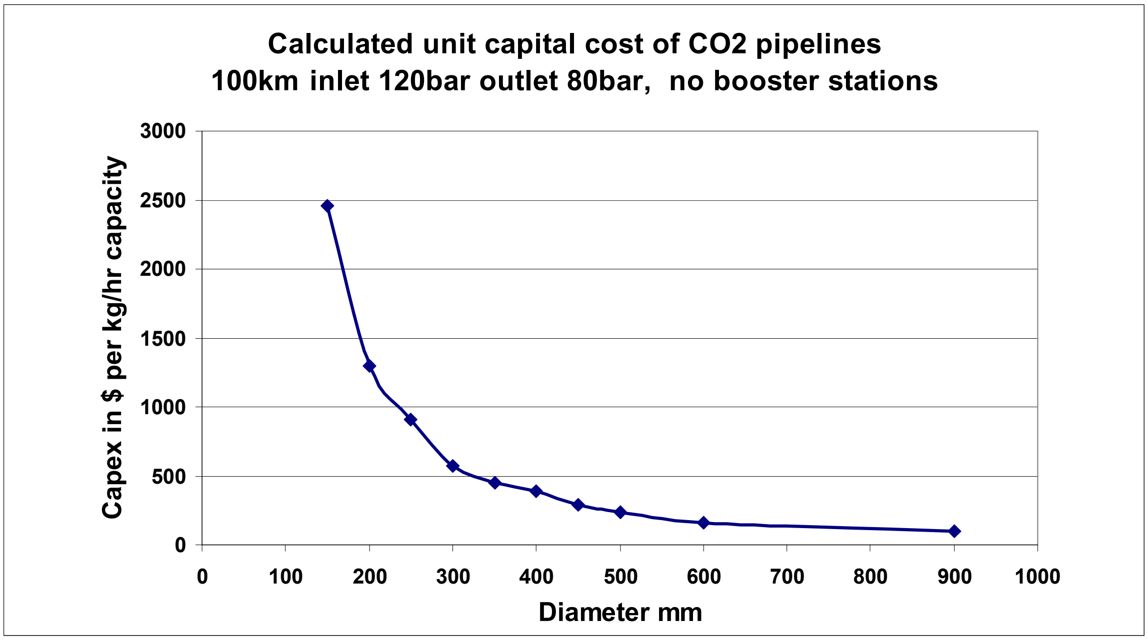

Fig2 Unit capital cost for a CO_2 line as function of diameter

The sizing routine was run with increasing flows which requires an increasing number of booster pumping stations. The effective unit capital cost of the capacity was calculated including operating costs discounted over 20 years. The results based on these costs from the model for installing and operating such pumping stations showed that pumping was in general a cheaper way of increasing capacity than installing larger lines. This is not a surprising conclusion given that pumping power and pump costs are much less than compression power and costs for gaseous systems. However although this analysis shows lower cost it would be operationally much more burdensome. The results for several sizes of line are shown in Fig 3 and 4 below.

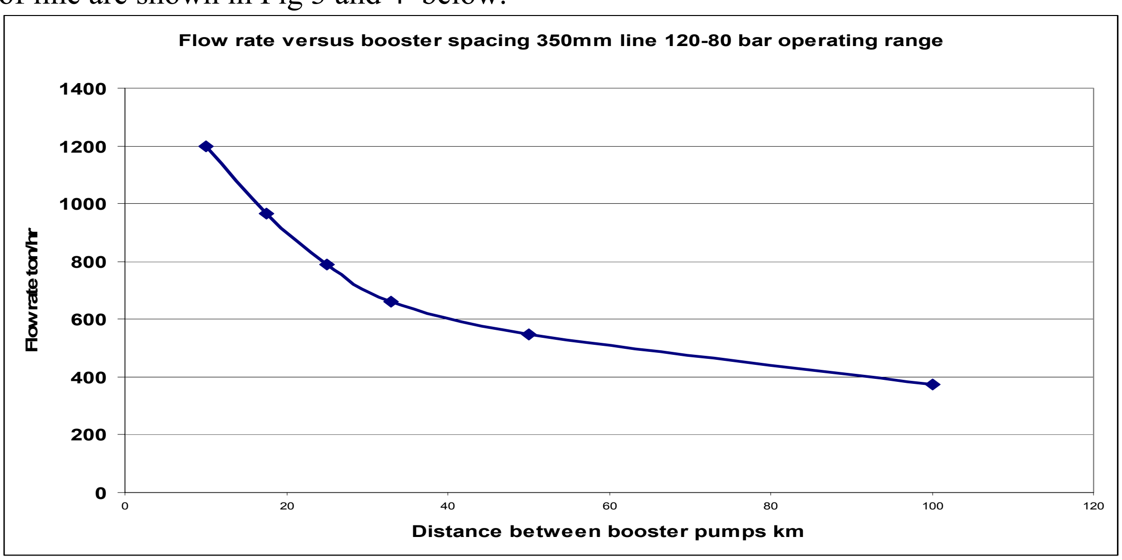

Fig 3 Variation of pipeline capacity with booster spacing

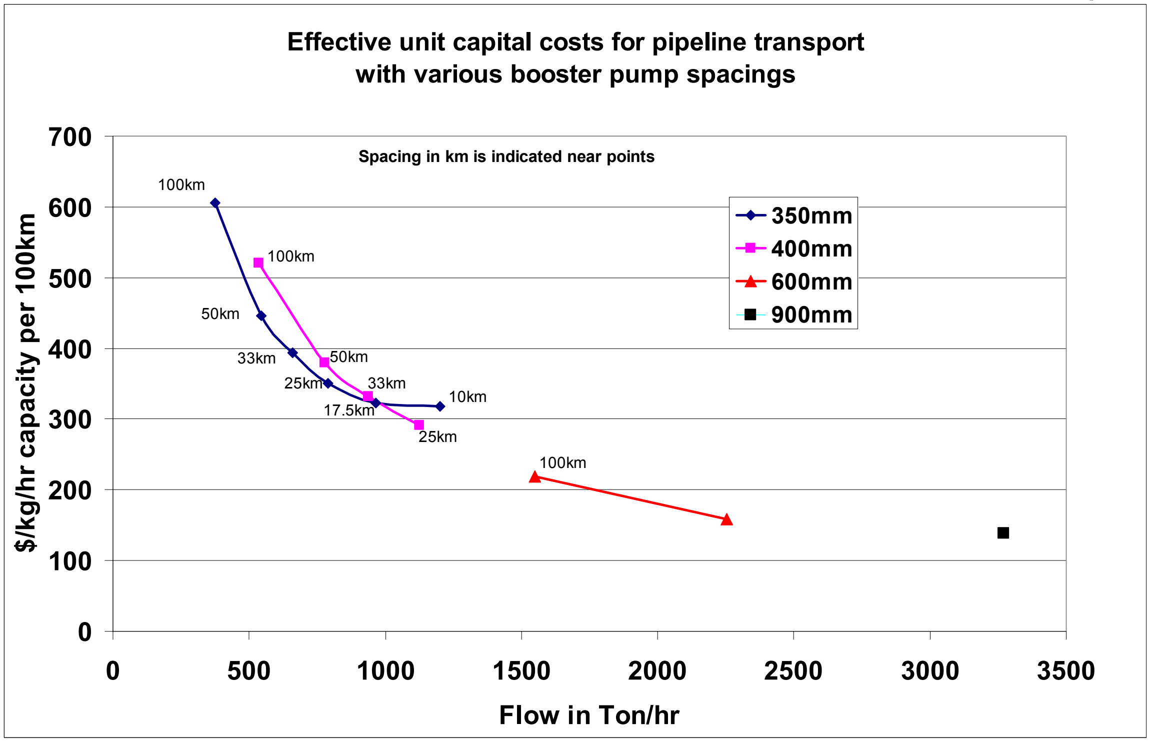

Figure 4 Variation of effective unit capacity costs with diameter and pump station distance

The last option now available is to design, size and cost low pressure distributed CO_2 collection networks. This is a stand alone part of the suite which uses the network design model developed by AMEC/Gastec-UK. Its main application is for the design of systems to gather CO_2 from clusters of smaller industrial sources of CO_2

Documentation for the calculator is in the form of the original built in help file plus a new guidance document explaining the changes made and how the user can use the additional features.

Expert reviewers comments

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The calculator was checked internally and not subject to formal external review. It is recognised from the internal reviews that the calculator needs to be used by experienced engineers and an AMEC project team has already used the new elements successfully for a major CO_2 collection infrastructure project as a test case

Conclusions

The revised cost and sizing calculator now allows more accurate high level sizing and costing of CO_2 pipelines and collection systems. It is not intended as a final pipeline design tool for which specialist pipeline sizing routines must be used able to cater for terrain height changes and the physical properties of the actual CO_2 gas compositions. The tool is now available for use. IEA GHG will maintain a log of comments and suggestions from any users so that any errors found can be corrected and useful improvements added if the amount of use and extent of suggestions warrants.

To use the revised model copy the excel file and help file which are in a subdirectory of the CD into the same directory on your computer. Open the excel file. Help on the basic functions is available through the help button or via the drop down menu (Cost Estimation Model.) Information on how to use the network design tool is to be found in a separate set of instructions in an appendix to this document entitled “Network model Instructions”. Information about the upgraded features is to be found in the report on the upgrade which follows this introduction

	GaC Contract No. 3626 AMEC Contract No. 1663A	
Project Upgrade of CO2 Pipeline Cost calculation Programs		
Document No. 1663A-020-000-RPT-001		Revision P

Upgrade of CO_2 Pipeline Cost Calculation Programs (IEA/COM/07/138)

P	Preliminary	JW	11/03/08					IRS	20/03/08
Issue Rev	Issue or Revision Description	Origin By	Date	Chkd By	Date	Appd By	Date	Appd By	Date
		AMEC						OTHER	

REVISION CHANGE NOTICES

Rev.	Location of Changes	Brief Description of Change
P	Original Issue	Original Issue

CONTENTS

FIGURES

1.0 INTRODUCTION

1.1 Project Overview

The IEA Greenhouse gas R&D program has two Excel based computer programs developed which estimate the cost of pipelines carrying CO_2. The first is a model built by Woodhill Engineering which includes routines for CO_2 trunk pipeline as well as for other fluids and also injection wells and capture plant. The pressure drop and line sizing routines in this model are considered to be inaccurate, especially under supercritical conditions.

The second model was recently developed by GASTEC at CRE Ltd and AMEC. This model calculates the costs of lower pressure CO_2 collection networks and is calibrated for UK costs. The purpose of the work is to upgrade both of these models and to integrate them into one.

1.2 Objective

The existing Woodhill program has a form based user interface whereas the Gastec/AMEC program is currently based on filling in a spreadsheet. In order to make the programs more user friendly a similar interface is required for this latter model.

In summary, the aims of the project are:

- to increase the technical veracity of the trunk pipeline model, and
- to improve the user interface amenability of the network model,

Thereby make them more complementary and better aligned to ensure seamless integration.

1.3 Integration Method

The resulting package does not fundamentally change the way the separate models worked. It is important not to disturb the coding and behaviour behind each model lest the validation of each part is lost. They have been integrated under the same visual style and a new control panel added, this is the only way the two models interact. The new trunk line routine is a stand alone calculation form which both models connect to, again to limit the interaction between models.

2.0 SCOPE OF WORK

2.1 IEA GHG Defined Scope

There were two defined activities with separate scopes of work. Firstly the modifications to the Woodhill programme, secondly the integration and refinement of the AMEC/GaC programme.

2.2 Woodhill Programme PH4-6

The Woodhill cost model enables costs of complete CCS projects to be estimated. As part of the model, trunk line segments for pipelines carrying CO_2/H_2 and natural gas can be calculated. The CO_2 pipeline cost figures generated by this model are considered insufficiently accurate. They use very simplistic assumptions about the fluid properties of CO_2 and use a very simple model for line sizing and costing.

1. Provide computerised information on CO_2 PVT and transport properties for use in accurate pressure drop and trunk line sizing to cover the full range of temperatures and pressures likely to be used in CCS projects. The range should be for pressures to at least 200 bar and temperatures from -20°C to +40°C.

2. Select a pipeline pressure drop and line size calculation routine suitable for dealing with long CO_2 trunk lines, compressible flow including supercritical conditions. It is expected that calculations will have to be based on splitting the lines into a number of sections because of the widely changing PVT conditions along the lines which are likely to be encountered.

3. Select a suitable basis for cost estimation of long trunk lines to include all the key parameters which affect cost including but not limited to:

   - Terrain type
   - World region
   - Steel price
   - Design margins
   - Compression stations
   - Additional features
   - Cost index

   For terrain type to be able to be specify % of each of several terrain types per segment.

   For world region to consider 4 or 5 main construction cost regions.

   For steel price to have a standard default value, (or values if each region is different).

Design margins refer to the different design stress margins applicable in areas of differing population exposure.

Additional features refers to such items as block valves, pigging facilities, leak detection monitoring.

Cost index refer to use a base index so that costs can be adjusted to allow for cost escalation with time. Use a separate index for pipelines and compression facilities.

4. Unlock the visual basic code used in the calculators (Password is case sensitive IEA2611). Re-programme the input sheet for CO_2 lines to include the extra input requirements and to allow for lines to be broken into appropriate number of segments. Note that the routines for Fuel/feed pipelines are to be left unchanged. Currently a selection of CO_2 or other gas is made on the pipeline branch input form. As the new CO_2 pipeline routine will be more detailed either a separate input form or additional detail on the existing input form will be required.

5. Re-programme the code to incorporate the new calculation routines. Calculations of each segment based on isothermal conditions. One temperature specified for each segment.

6. Modify the output sheets to reflect the additional data generated.

7. Include a graphical representation of pressure and density conditions along the line segment.

2.3 GaC/AMEC programme

The routine produced by Gastec/AMEC covers only UK construction costs. The work will include extending the programme to cover costs in a number of other regions. In addition the costs for compression stations should have the option for stand alone or being integrated on site with capture facilities. At present they assume a stand alone site has to be provided.

1. Collect data necessary to use the existing model for a selection of other world regions. Group countries by region. Use 5-6 regions.

2. Modify programme to allow selection of alternative regions

3. Include cost index calibration point with possibility for users to apply a suitable global escalation index.

4. Define default currency exchange rates which are applicable at the time of set up. For each region select an appropriate currency in which results are reported by default, £, € and US$ should suffice. Include option to report in alternative currency using the fixed default exchange rates, which shall be displayed.

5. Integrate the spreadsheet into the Woodhill model calculator and add input and output form or forms of similar style and appearance. Ensure that the worksheets in which data are entered are also accessible e.g. with a toggle so that they can be viewed.

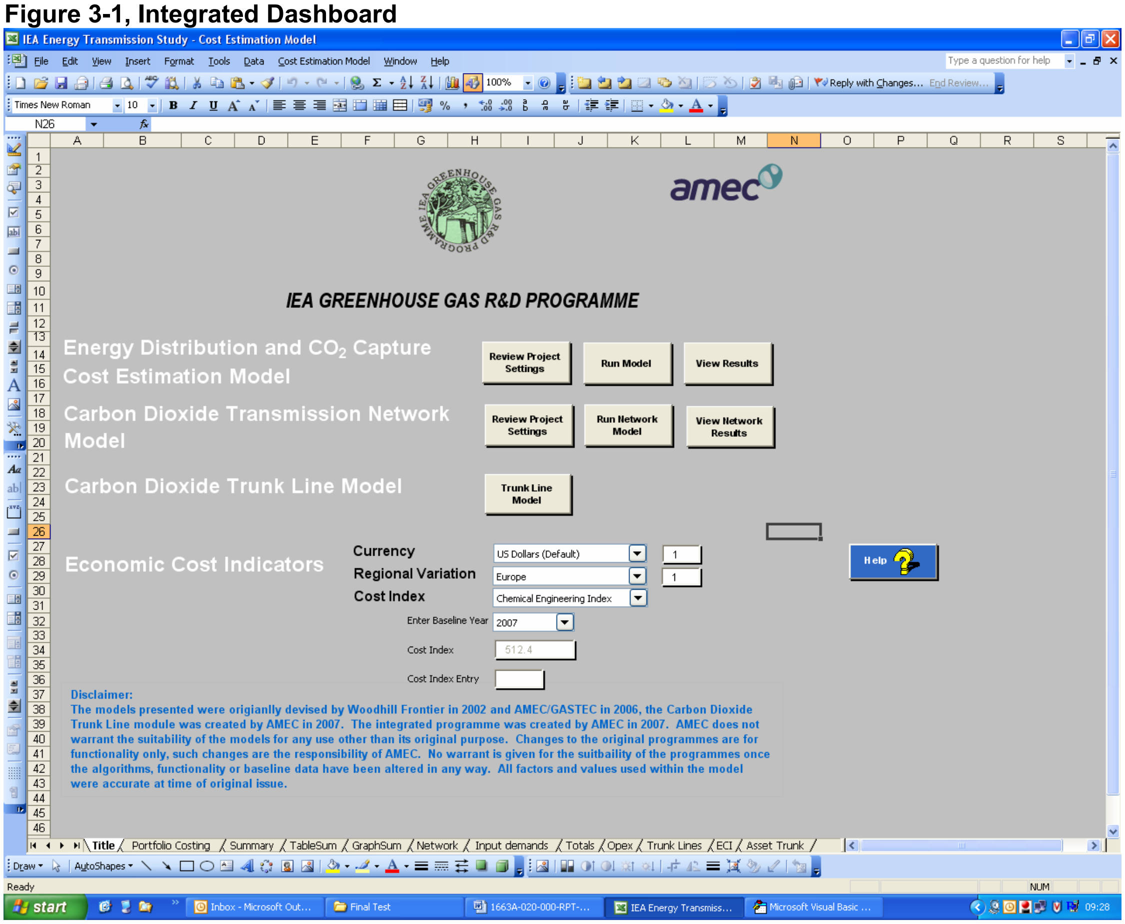
3.0 Introduction to the models and the integrated package

The new model consists of three parts;

- Energy Networks – the Woodhill Model
- Carbon Dioxide Network – AMEC model
- Trunk Lines

Each is a distinct part to the model with limited interaction. The models are accessed by a simple dashboard, Figure 3-1, directing the user to the models and the cost index tool now included.

Figure 3-1, Integrated Dashboard



Selections can be made form the dashboard to edit settings, view results and run the model. Project settings for the network model are also the project settings for the Trunk Line model. Once selected the model runs as per the original model with the minor modification operating alongside.

4.0 Changes to the network model

4.1 Network model inputs

The major change to the original network model is cosmetic, the previous format has been updated to provide a consistent format over the whole model. As part of this the input format has been changed slightly with project wide variable being consolidated in one place. The network model section is now three forms;

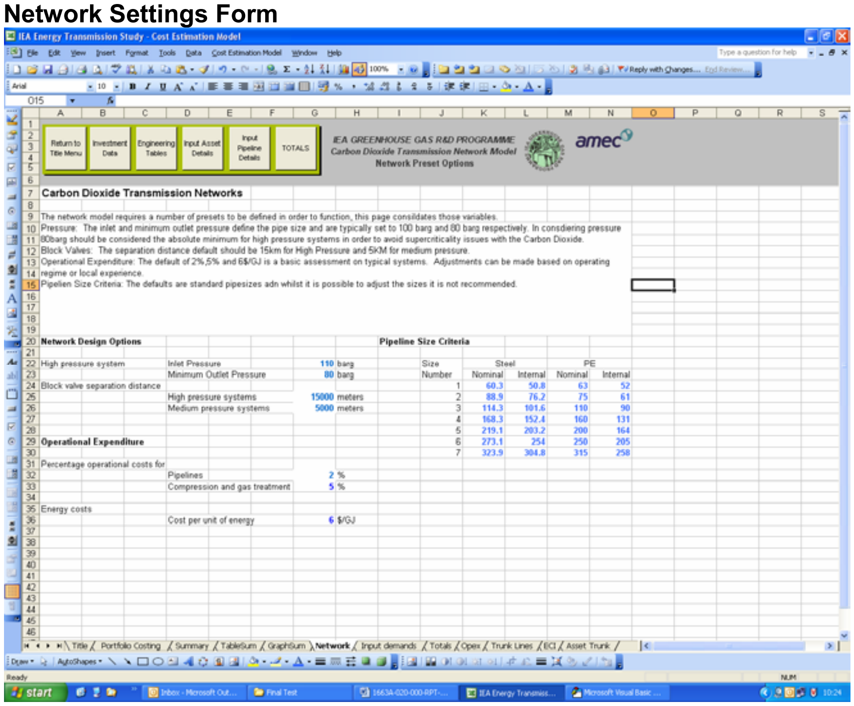
- Network – sets the default values and conditions
- Input Demands – data entry for emitter information and low pressure elements of a network.
- Input Pipelines – data entry for the network pipelines information

Reference should be made to the original models' reports for operating instructions in greater detail.

4.2 Network

The network page, Figure 4-1, allows the user to adjust the network models defaults for operating pressures, block valve distances and operational expenditure variables. Pipe sizes are also included on this page, but it is recommended that no changes be made to this table.

Figure 4-1, Network Settings Form

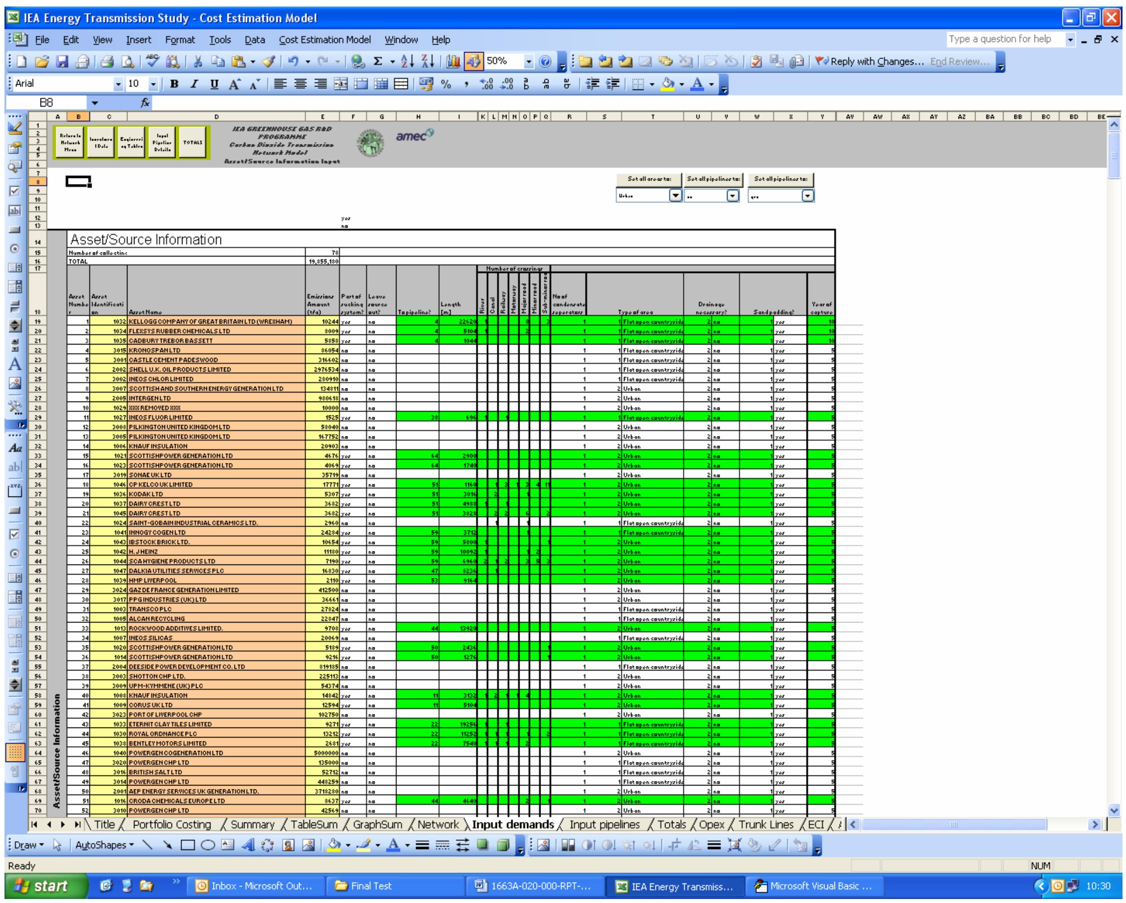


4.3 Input Demands

The input demands form, Figure 4-2, is unchanged from the previous model apart from the cosmetic formatting. Here emitters are added and selected for low pressure service or into medium or high pressure routes.

For suction sources the pipeline length, crossings and terrain information s added and the model provides a pipe size. This information then feeds into the CAPEX model.

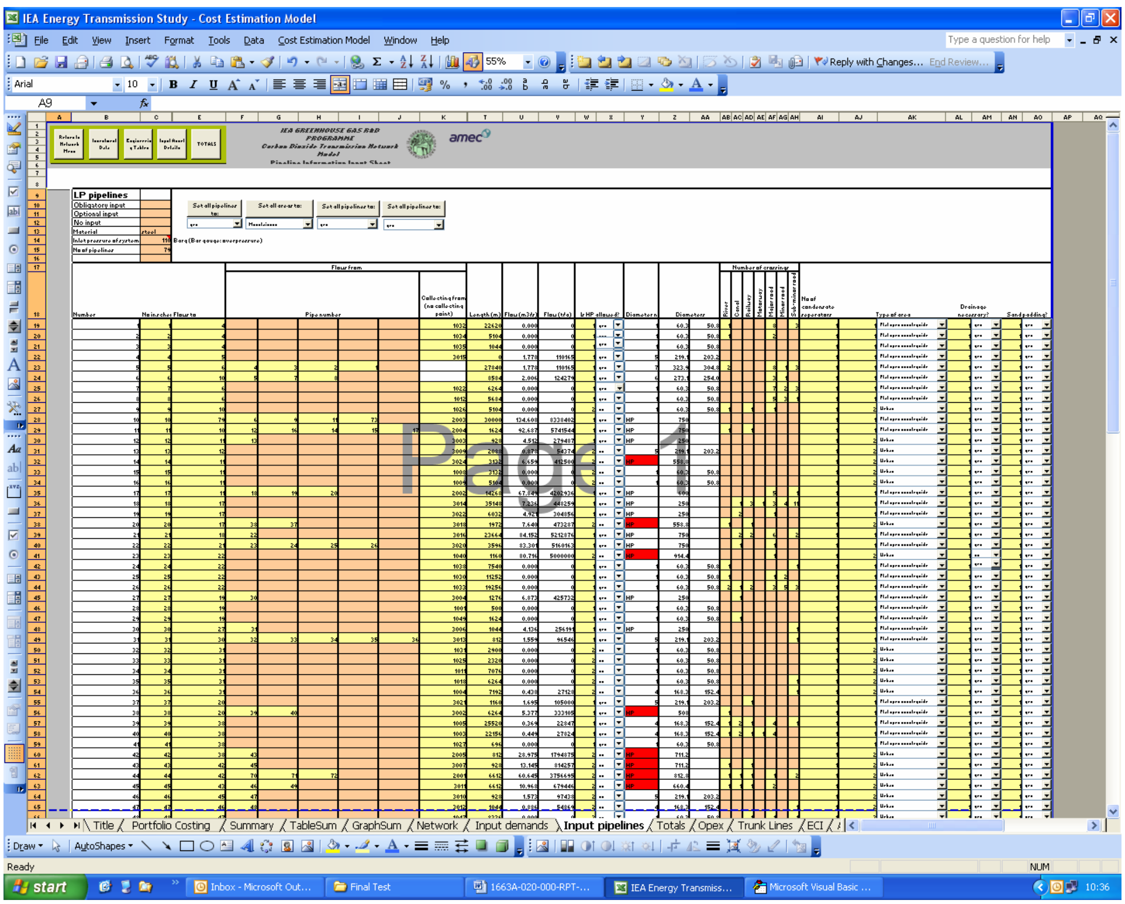
Figure 4-2, Input Demands Form



4.4 Input Pipelines

As with the previous page the changes to this sheet, Figure 4-3 are cosmetic. As before this sheet uses the emitter's ID number and the pipeline number to construct a network and size the entire network rather than the pipelines individually. As well as data entry this form also provides the results, in the form of line sizes.

Figure 4-3, Input Pipelines Form



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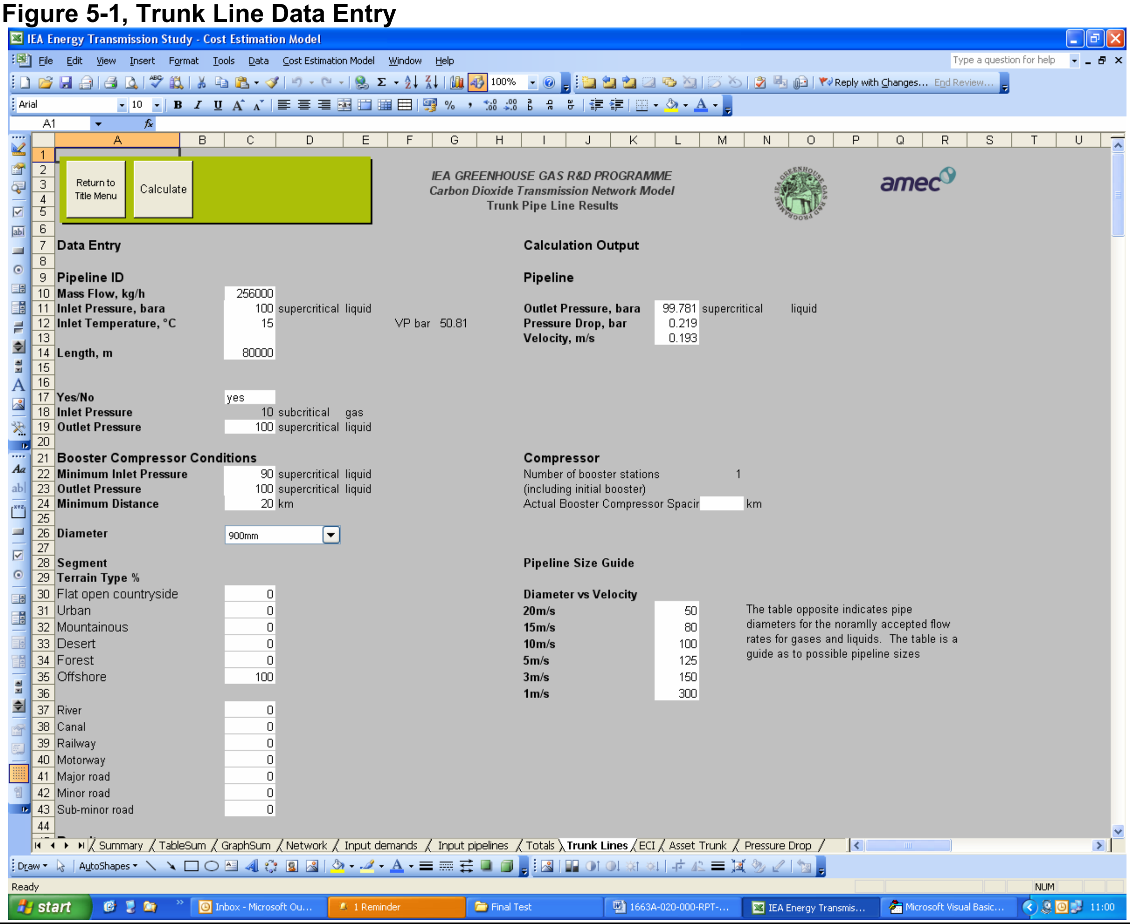
5.0 Trunk line model

5.1 User Interface and Operation

The trunk line model is new and allows a single large pipeline to be considered in conjunction with a network from either model. Suitable for both Offshore and Onshore operation, the trunk line considers a long pipe in more detail than either of the previous models, splitting a pipeline into 20 segments and performing a segmental analysis of the pipeline.

The user inputs data in to the clear fields on the form, Figure 5-1, and a sizing routine will size the pipeline, calculate the pressure drop, operating conditions, compressor size and number and provide a cost estimate. It is possible for the user to manipulate the pipeline size to optimise the size required, the model does not automatically calculate the diameter this must be selected. The indicative table “Pipeline Size Guide” indicates the appropriate size for a preset velocity. For CO_2 systems it is recommended that the usual flow conventions apply, a maximum velocity of 20 m/s in the gas phase and 3 m/s in the liquid or supercritical phases.

Figure 5-1, Trunk Line Data Entry



5.2 Booster Stations

The model calculates the requirements for both the Initial Booster and Pipeline Booster stations should they be required.

Whilst initial pressurisation for a network would be covered within the network model, standalone pipelines or pipelines with long cross country runs may operate at higher pressures. If they do operate at higher pressures, then an initial booster will be required. The inlet and outlet pressures are allowed to transition the phase boundary however it is recommended that the outlet pressure is not specified below 90bar to avoid two-phase transition or flow in the pipeline.

For onshore pipelines it is often more efficient to provide periodic booster stations on a pipeline to maintain the pressure rather than run large low pressure drop pipelines. If this is the case then the model will calculate the number required and the distance between stations. For offshore pipelines the provision of boosters along a pipeline length is not practical as this would require entire offshore installations to be provided at a significant cost. Therefore offshore pipelines are best pressured at the beach and at the destination only. To provide for this condition the initial booster should have a high enough outlet pressure to ensure that the entire pipeline length remains above 90 barg. The model does not however calculate the power or cost of an offshore compressor installed in an existing structure for local well head pressure boosting.

The user simply has to set the Booster Station details selecting an inlet and outlet pressure or a minimum distance between stations. Using these criteria the model assess each segment of the pipeline and adds a booster station when the pressure drops below the compressors specified inlet pressure.

5.3 Terrain and Crossings

Terrain and crossing information is added to the model to adjust the costs accordingly. For terrain the percentage of terrain type for each pipeline should be added, taking care to ensure that it totals 100%. This methodology applies a factor based on the percentage to the pipeline cost. Crossings are added as the actual number of crossings of each type.

For offshore pipelines the offshore terrain should be the only terrain selected and the number of crossings should be zero.

5.4 Pipeline calculation

The pipeline calculation is based on a segmental approach dividing any pipeline into 20 distinct segments. Each section is subjected to the calculation routine and incorporated in the results. This approach gives a slightly more accurate approach than assuming one segment for the whole of the pipe as it allows at each segment the transport conditions to be correctly considered.

The methodology used is fairly robust and has been tested against established process simulation packages Aspen Plus and Hysys. The formula used in the calculation is used in the pipeline for both gas and liquid and it was found that by assuming isothermal conditions the same equation could be used for all physical states that may be experienced.

The formula in the general form is;

$$W^2 = \left[\frac{g \times d \times A^2 \times \rho}{f_F \times L}\right]\left[\frac{\left(P_1^2 - P_2^2\right)}{P_1}\right]$$

Where,

W = mass flow, kg/h

d = pipe internal diameter, mm

f_F = Moody friction factor

L = pipe length, m

P_1 = absolute inlet pressure, bara

P_2 = absolute outlet pressure, bara

ρ_1 = inlet fluid density, kg/m³

And the following assumptions are made;

1. Isothermal flow occurs.
2. No mechanical work is done by the system and no mechanical work is done to the system.
3. Steady flow inside the pipe occurs.
4. The gas being conveyed is Ideal.
5. Velocity may be represented by average velocity at a cross section.
6. The friction factor being applied is constant along the pipe.
7. The pipe is straight and horizontal between the end points.
8. Acceleration can be neglected because the pipe is long.
9. Substance contained within the system assumed to be pure carbon dioxide.

The calculation examines each segment in turn and uses the previous segments results to drive the equation. As a value drops below the minimum allowed the routine adds a compressor and calculates the size and cost.

5.5 Costing

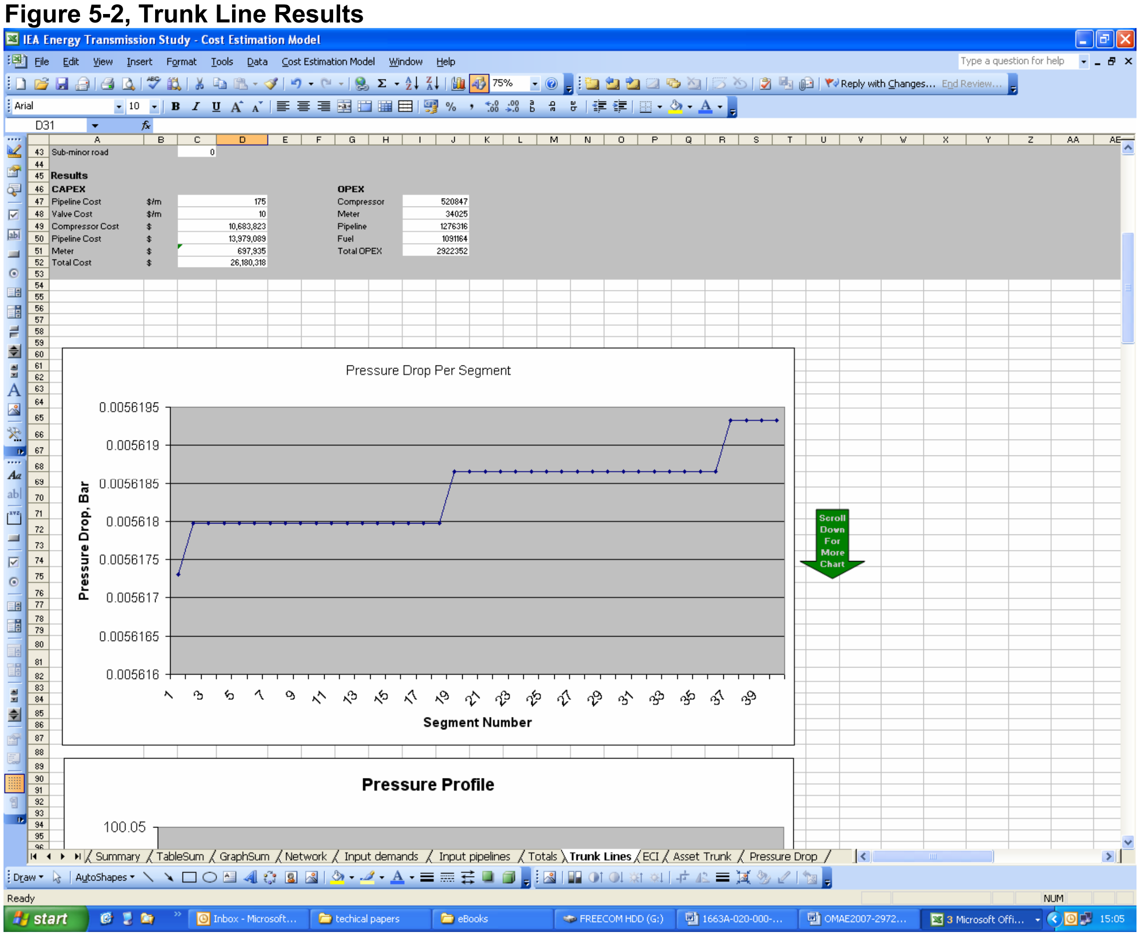
Costing of the pipeline uses the same cost information as the network model and the same factors. The trunk line model works by costing a pipeline and then applying factors according to Terrain, crossings, valves, cost indices changes and regional variations. There are no variables that can be manipulated for the trunk line model alone.

5.6 Results

The results are summarised at the bottom of the data entry table in the form of separate CAPEX and OPEX figures as illustrated below, Figure 5-2. Following this is a number of graphs;

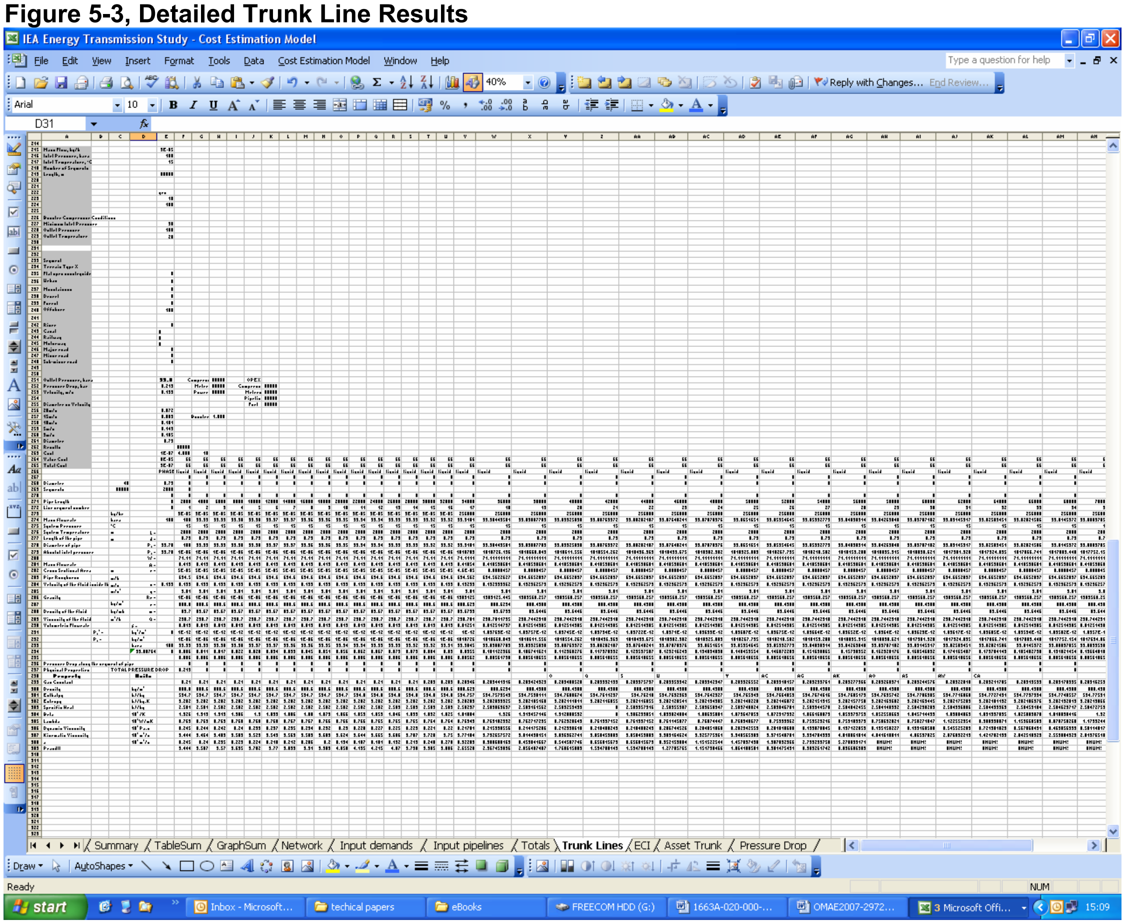
- Pressure Drop per Segment
- Pressure Profile
- Pressure Drop Profile
- Density Profile

Figure 5-2, Trunk Line Results



In addition to the graphs the bottom of the page contains more detailed information, a copy of the calculation results by segment, Figure 5-3. This allows a competent user to examine the pipeline in detail and make changes to the input accordingly.

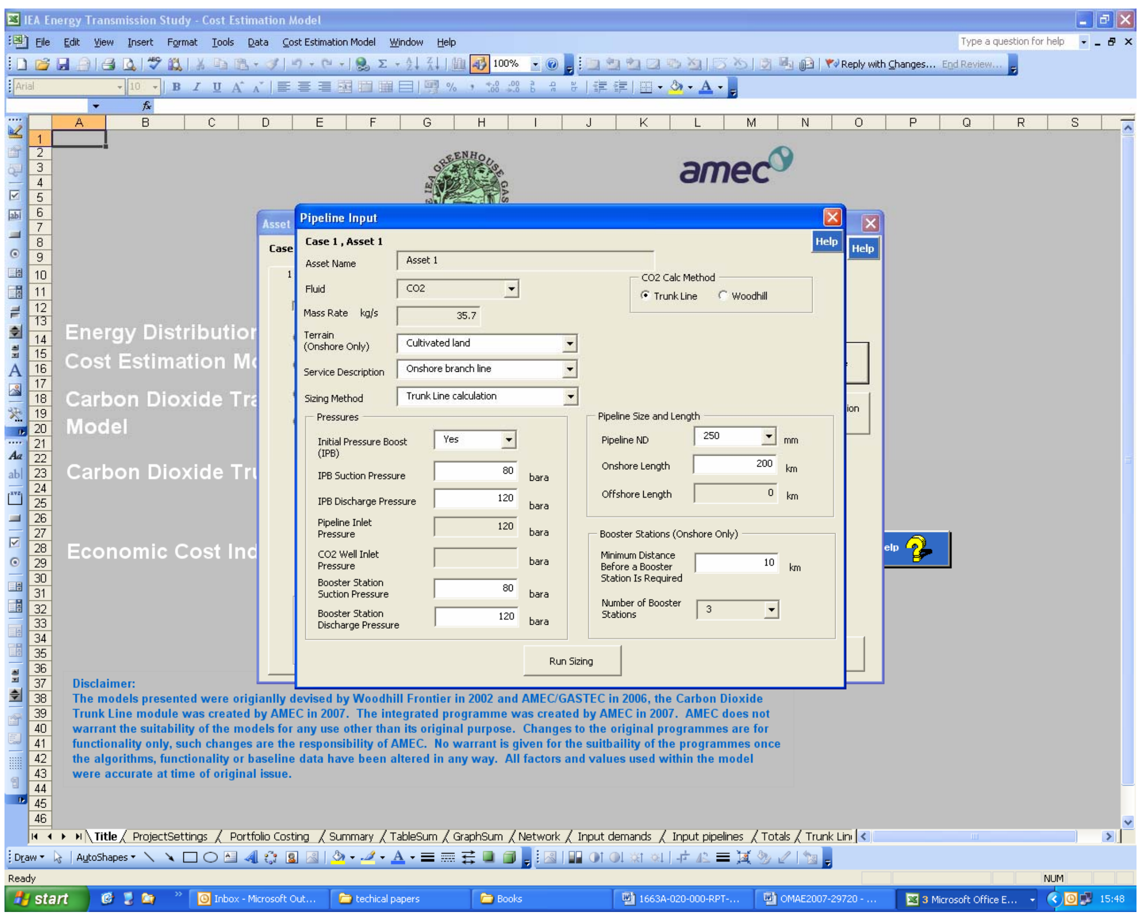
Figure 5-3, Detailed Trunk Line Results



5.7 Interfacing with the Woodhill Model

The Woodhill model previously used a set of fixed terms in its pipeline calculation. It is now possible to select either to use the previous methodology or select the AMEC trunk line calculation. The pipeline calculation entry form, Fig 5-4, has been modified to allow selection. Data entry is the same however by selecting “Trunk Line” the model applies the new methodology and reports the data back to the model in the appropriate format.

Figure 5-4, Woodhill Model Pipeline Calculation Form



6.0 Economic Cost Indicators

The model now includes three economic factors, the first a regional variation, currency variation and a set of engineering cost indices. The regional variations are basic are simple multiplication factors to the baseline cost.

Table 6-1, Regional Cost Factors

Region	Cost Factor
Europe	1
UK	1.2
USA / Canada	1
South America	0.8
North Africa	0.8
Equatorial Africa	0.9
South Africa	0.7
Russia	0.7
Middle East	0.9
Indian Sub-cont.	0.7
SE Asia(excl.Japan)	0.8
Japan	1
China / Central Asia	0.7
Australia / NZ	1

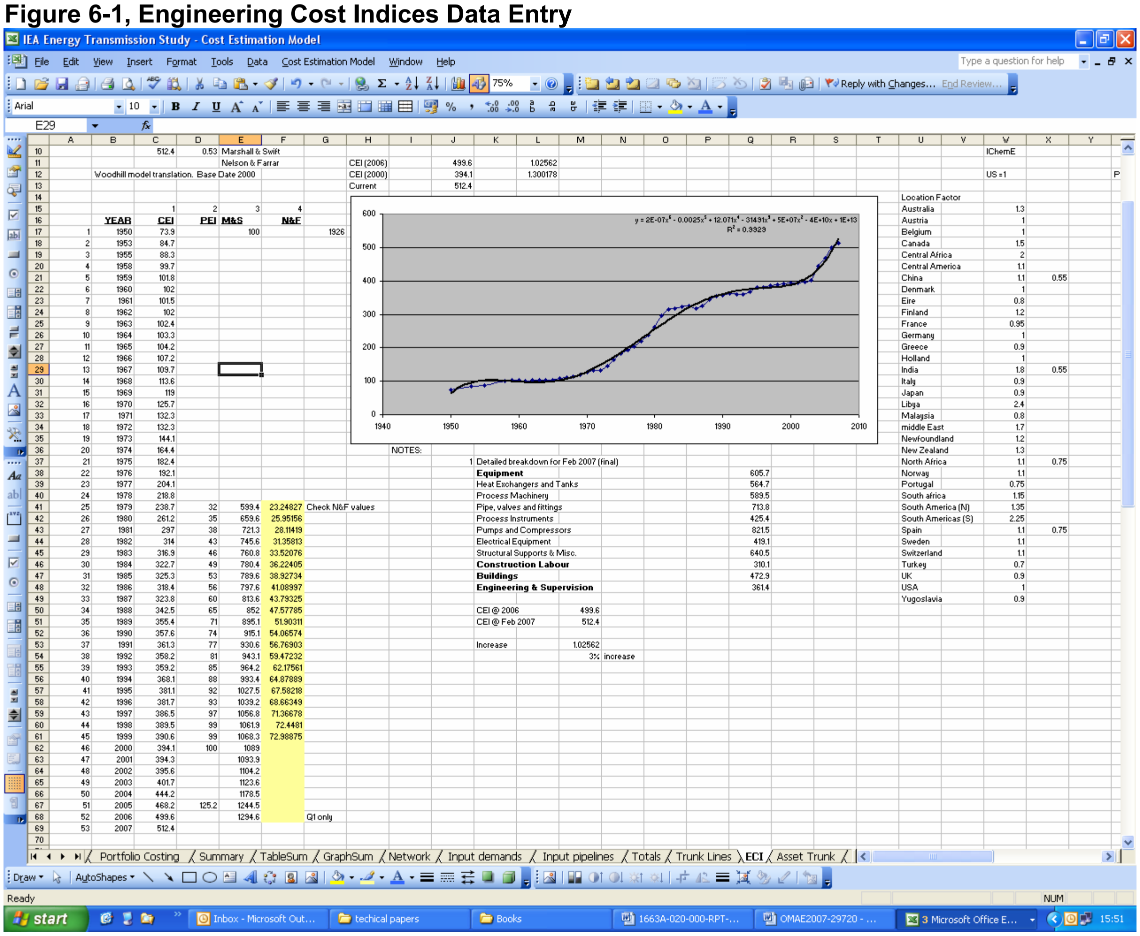
Similarly currency factors are simple multiples.

Table 6-2, Currency Factors

Currency	Factor
US Dollars (Default)	1
Aus Dollars	1.21465
Euro	0.74955
Yen	117.86
UK Sterling	0.50985

For cost indices a number of systems are provided whilst partial data sets for Marshall & Swift and the Process Engineering Index are provided it is recommended that the Chemical Engineering Index should be used. The facility exists to edit or add to this data set as it becomes available by means of the sheet "ECI", Figure 6-1. This information is not however publicly available and journal subscription is generally required to access up to date indices.

Figure 6-1, Engineering Cost Indices Data Entry



Appendix – Network Model Instructions (Extracted Appendix 6 of report 2007/12)

Appendix 6: Spreadsheet Instructions

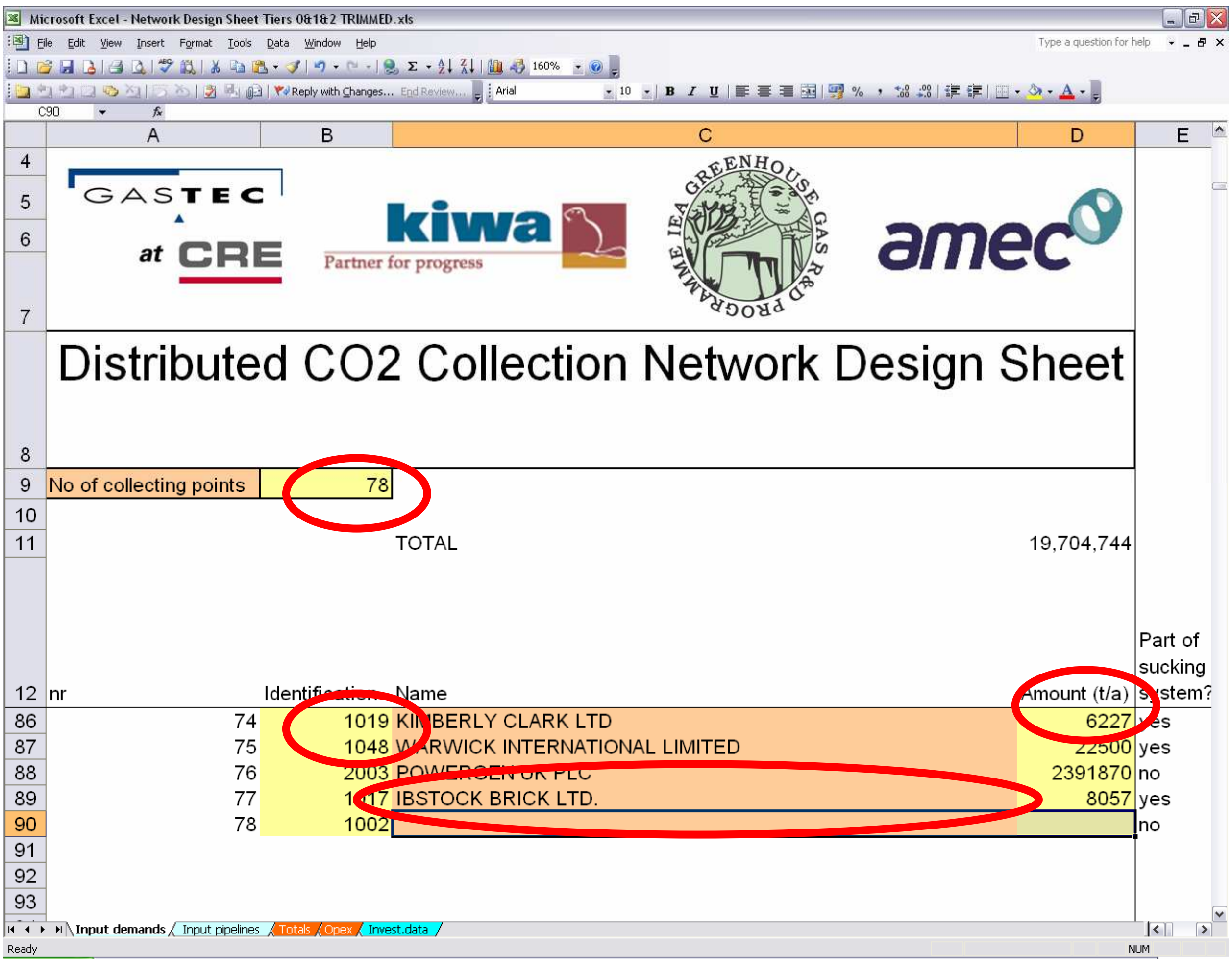
The following section is a simple step by step guide intended to aid network designers who wish to use the design spreadsheet.

The spreadsheet will only tell a designer what size/material of pipe is required, pressures and costs, however a number of design decisions still need to be made. Prior to using the spreadsheet, the shape of the network to be designed should be determined and pipeline connections and distances should be established in the usual manner.

First of all, open a copy of the spreadsheet and save it under a new name e.g. Network1.xls. Now follow Steps 1 – X carefully to design your network.

Step 1: Input Emission Sources

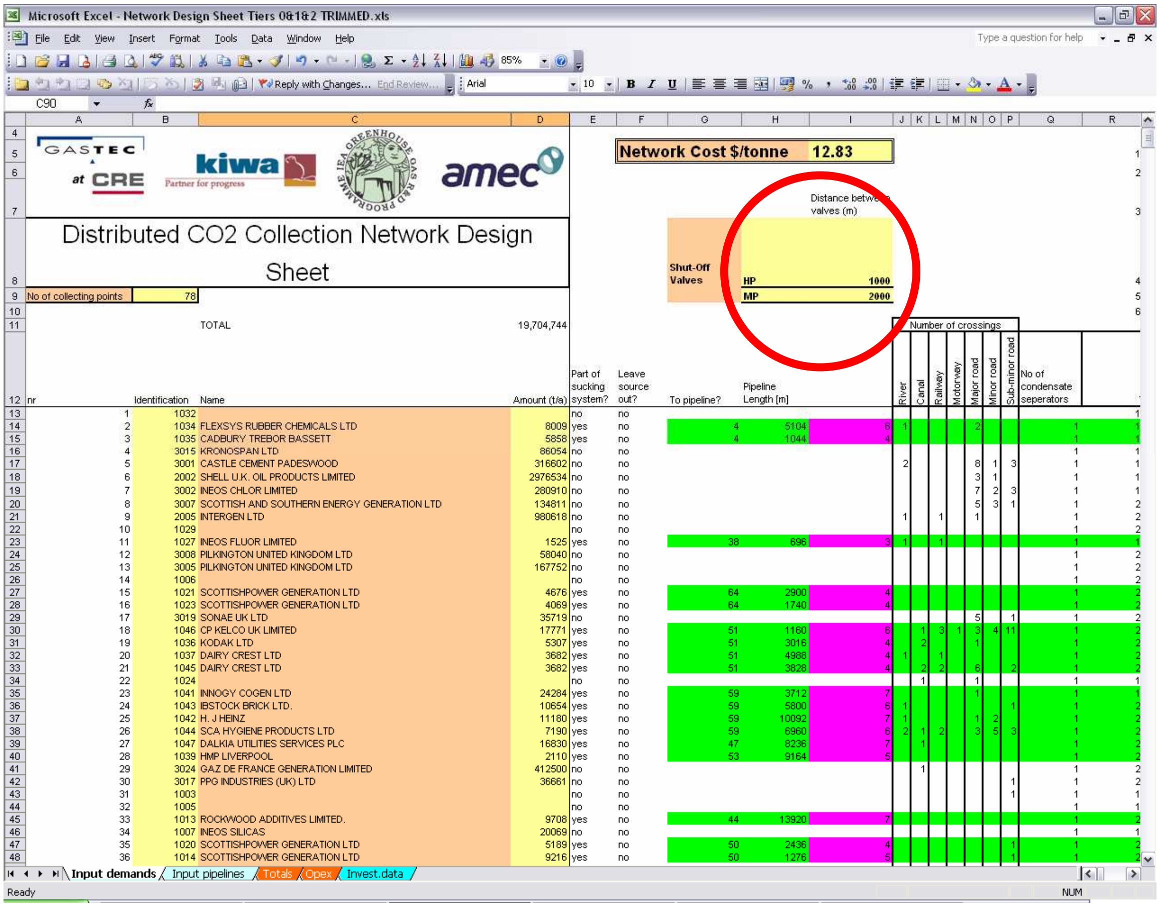
Ensure that the **"Input Demands"** tab is open.



Input the total number of sources to be included within your scheme in the yellow box next to "No of collecting points". Next input the name of each source and give it a unique identification number e.g.

1001, 1002 etc. Input the emission (total to be collected) from the source in the column to the right of the name.

The distance required between shut-off valves can also be entered on this tab. Default values applicable to the United Kingdom are already set, but these can be altered.

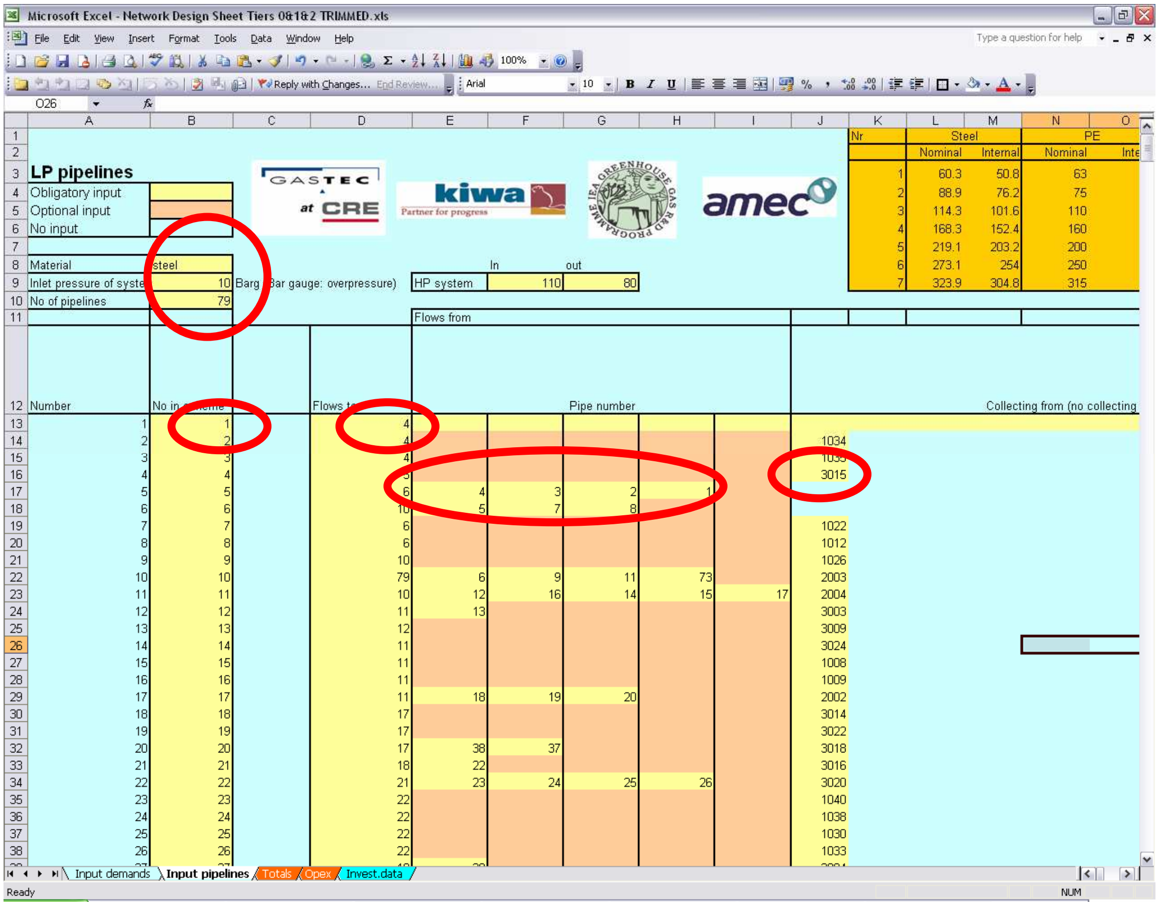


You will notice that there are further columns to the right of those that have been filled in, ignore these for the time being and proceed to the next step.

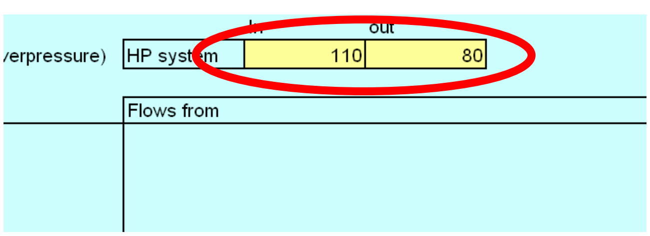
Step 2: Input Pipe Distances and Connections

Ensure that the **"Input Pipelines"** tab is open.

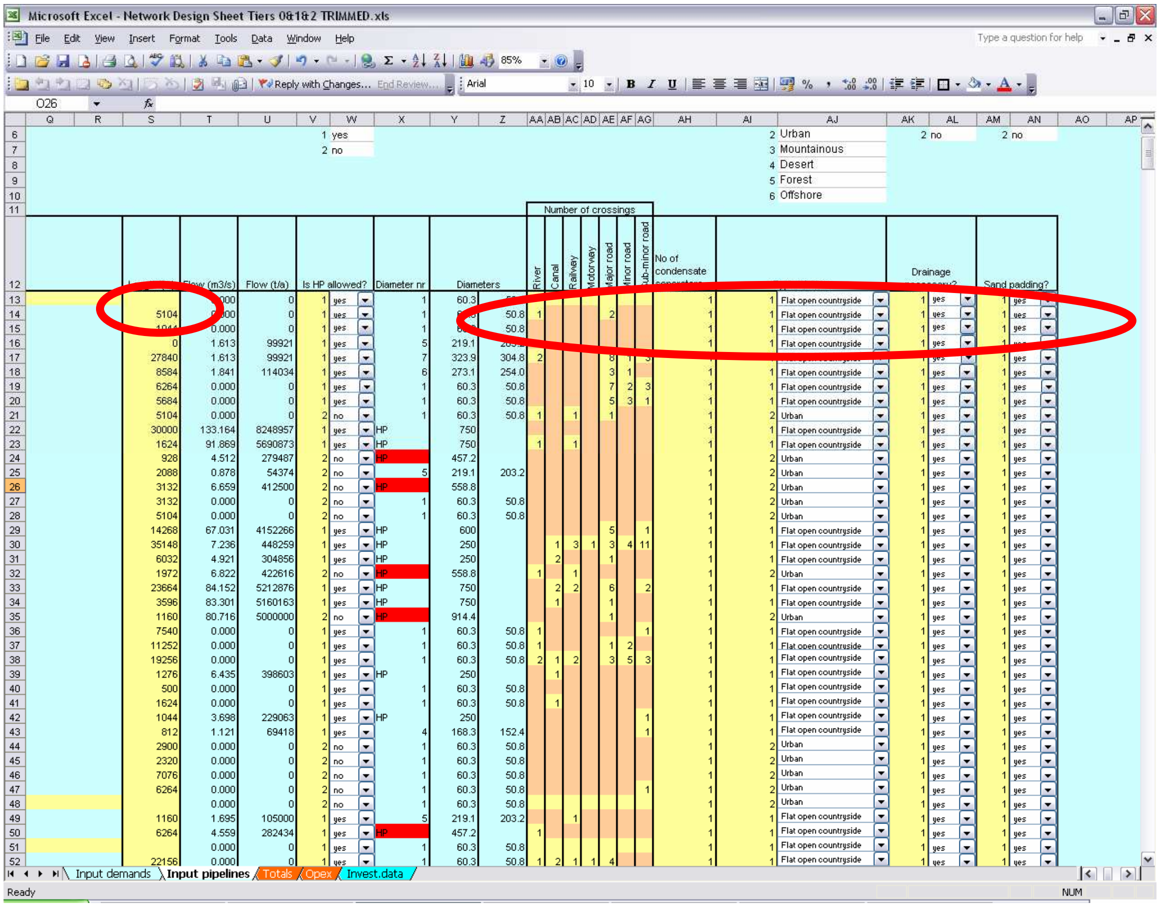
Input the number of pipelines within the proposed network, the inlet pressure of the system and the materials of construction; this will open up the appropriate number of lines on the sheet for pipes.



For each pipeline input it's allocated number in the scheme, any pipes that the pipe flows to (for pipes that flow out of the network input "0") and pipes that flow into that particular pipe. If a particular pipeline collects CO_2 from a source in the network, input the source ID (e.g. 1001, 1002) into the "Collecting from (no collecting point)" column. The inlet and outlet pressure of the high pressure system can also be input. The default values ensure that the CO_2 is in the supercritical phase.



Next input the length of the pipeline, the predominant terrain that it crosses, any major crossings (e.g motorways etc) the number of condensate separators, and whether drainage or sand padding is required for the pipeline.



Note that if a pipeline crosses several different types of difficult terrain it is advisable to split it into several smaller pipes to gain an accurate cost for that section.

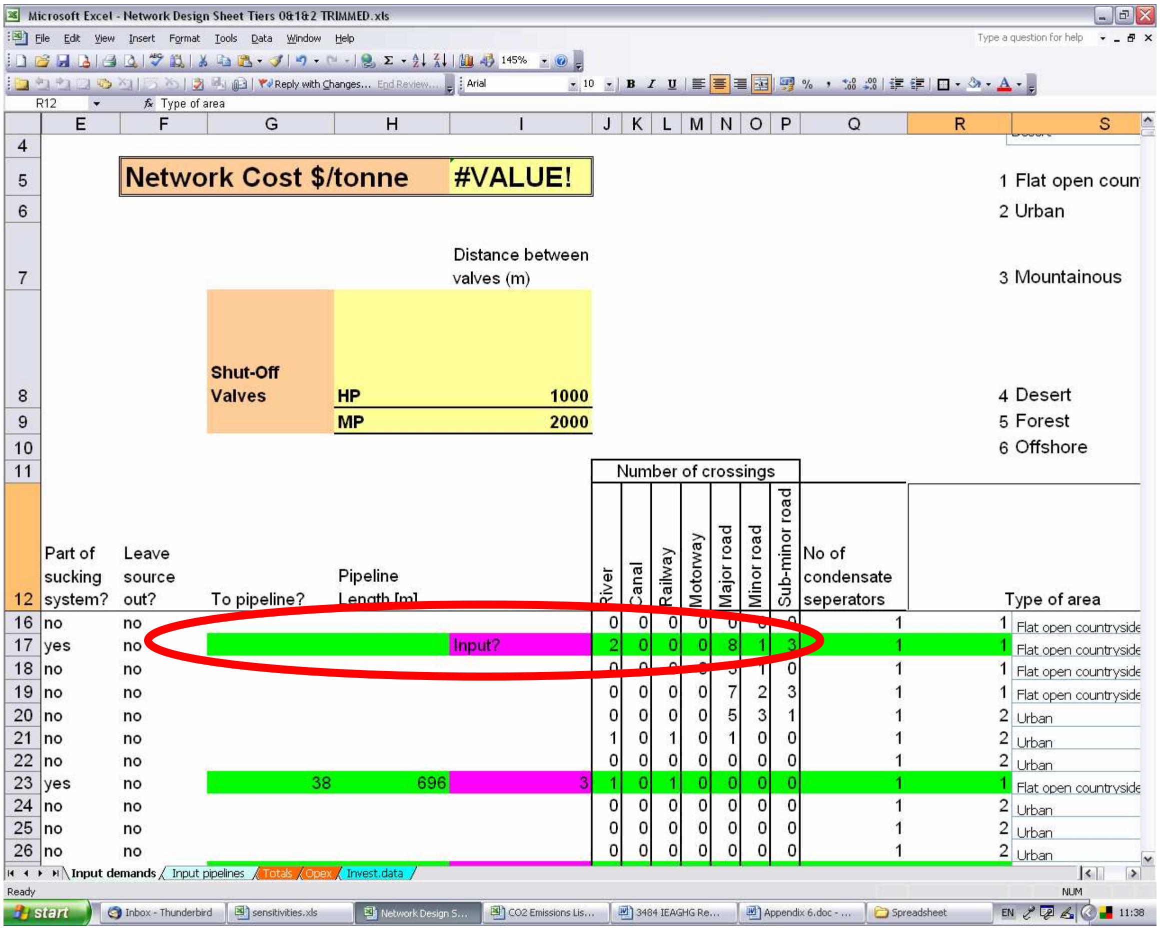
The default setting for the spreadsheet is to not allow high pressure lines in urban areas. This setting can be changed just above that column by setting all lines to yes (allow HP).

Care should be taken to ensure that all lines are entered correctly. Any mistakes in the data will affect the spreadsheet output. Once all data has been entered proceed to the next step.

Step 3: Input Suction Network

Ensure that the **"Input Demands"** tab is open.

You will notice that the information relating to crossings etc has been transposed to this sheet. You can now select parts of the network to operate under a suction system. Choose a source to be included in the suction network and select "yes" in the "Part of Sucking System?" column. Some of the columns to the right of the source will change colour.



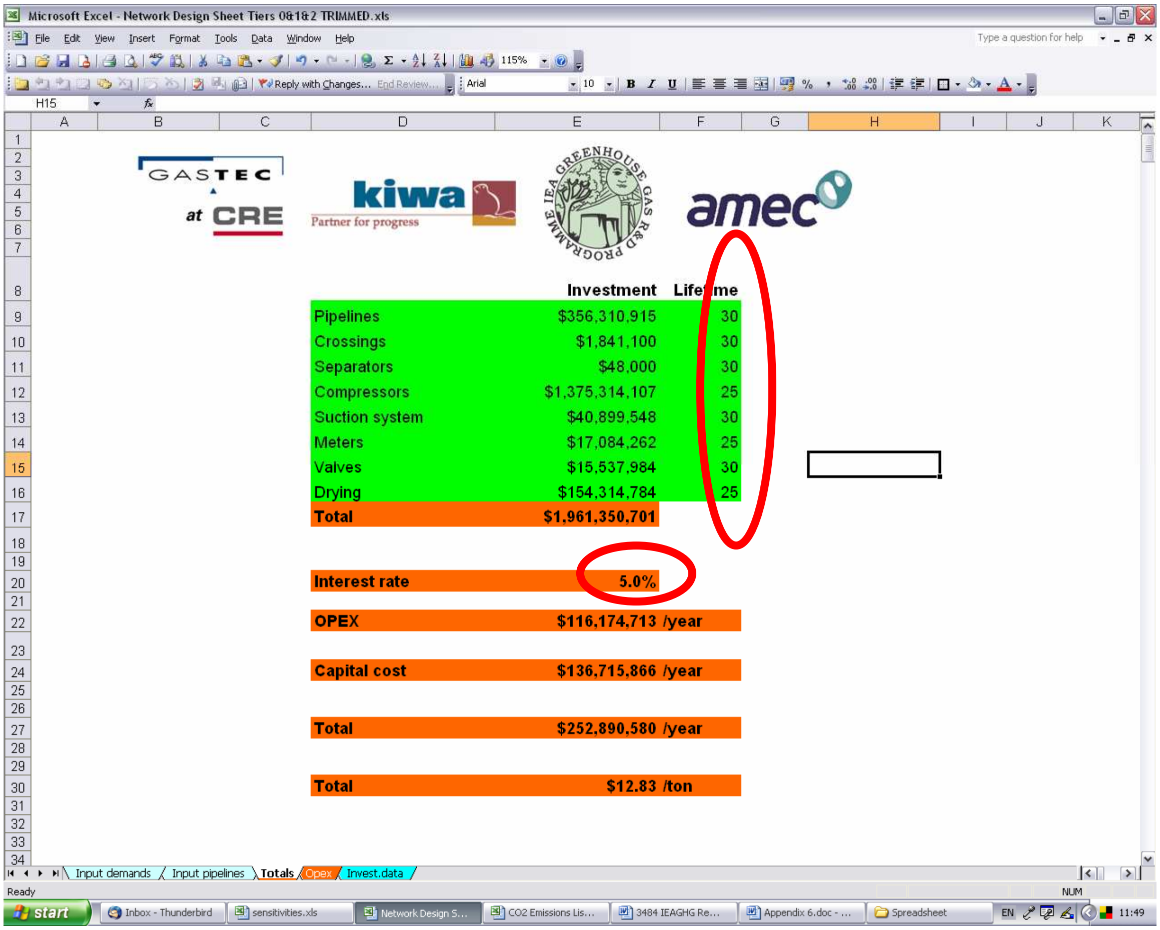
Input which pipeline the suction system is connected to for example if pipeline 1 is to be under suction and is connected to pipeline 2 you would enter a 2 in the "To pipeline?" column. Enter the length of the pipeline in the adjacent column. The purple column should now change; if it reads "n.a", then a suction pipeline is not possible for this source either because of the size of emission or the distance to be travelled means that the pipe required is too large. If a suction pipe is not feasible for a particular source ensure that the "Part of sucking system" column is returned to "no".

Once this stage is completed all information relating to sources and pipelines should have been entered into the spreadsheet.

Step 4: Interest, Plant Lifetimes and Operational Costs

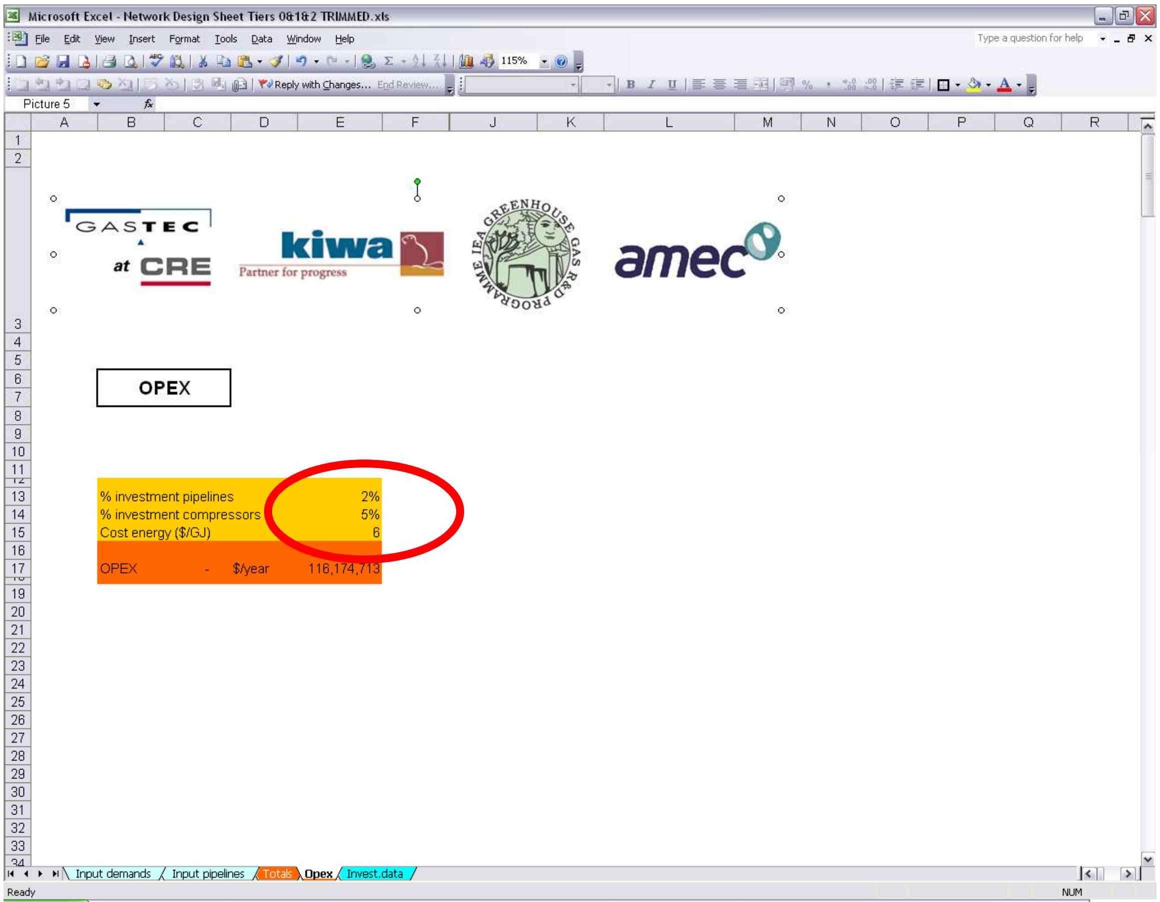
Ensure that the **"Totals"** tab is open.

From this tab the plant lifetimes and interest rate can be changed depending upon the particular circumstances applicable to the network being designed.



Next ensure that the **"Opex"** tab is open.

From this tab the operational costs can be estimated. It is possible to change the percentage operational cost from capital cost and the cost of energy for compression.



Your network should now be complete.

The total cost of transportation for the network per tonne of CO_2 is displayed on the **"Totals"** tab and the **"Input Demands"** tab.