Department of Mechanical and Aerospace Engineering

Modelling Water Distribution Networks to determine potential energy recovery using ESP-r

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Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Michael Rintoul Date: 7/9/12

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Abstract

The water industry is required to provide adequate pressure levels for all of its networks. This is most commonly achieved through the use of break pressure tanks or the use of pressure reducing valves (PRVs) within its piping networks which convert constant or variable inlet pressure to a predetermined constant outlet pressure. By replacing PRVs with small scale hydro there is the potential to capture this pressure loss and generate power thereby reducing energy consumption within water distribution networks and reducing leakages simultaneously. The aim of this thesis is to develop a tool which allows the user to determine the energy potential of a water network which uses PRVs or break pressure tanks to build a cost analysis of installing energy recovery technologies for water utility companies. The computer modelling software ESP-r was used to create a model based on an existing distribution network Perthshire, Scotland. Using the mass flow solver within the ESP-r program, the network was analysed and a spreadsheet was developed to calculate the energy available and carry out a cost analysis. Further investigation covered expansion of the network, pipe diameter selection, temperature variation and turbine efficiency. The model showed that installation of small scale hydro could be made viable following the expansion of the current network into Perth, increasing electricity generation significantly. The method used can be a basis for any water network which uses break pressure components.

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Introduction

Since 2004/05 electricity use at Scottish water has risen by approximately 40GWh fallen by 35GWh by 2010/11, illustrated in Figure 1 below (Scottish Water 2011).

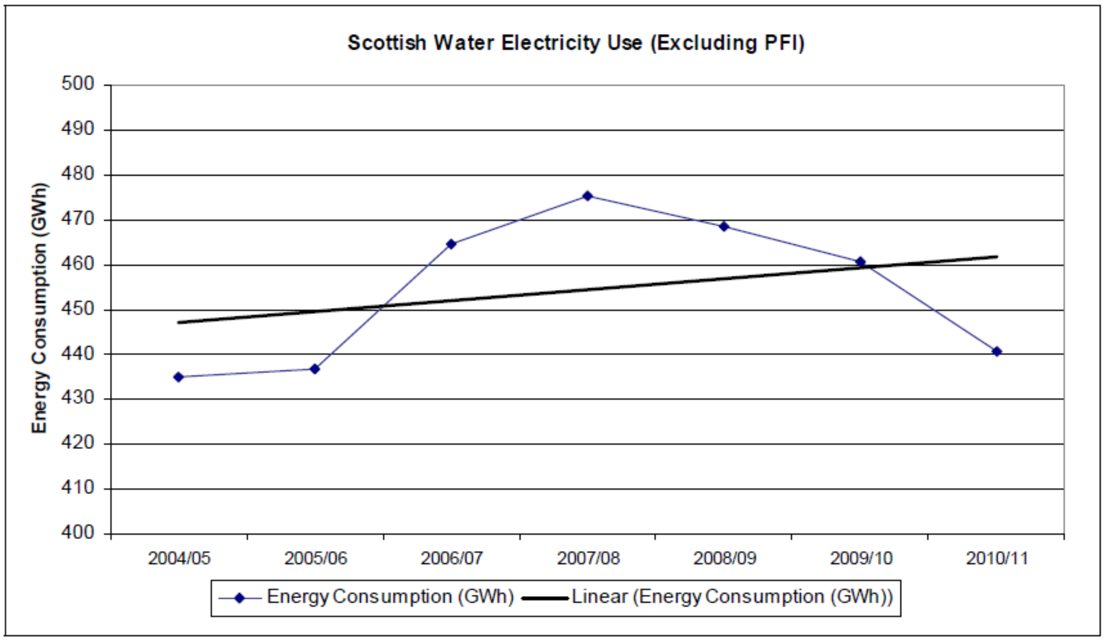


Figure 1: Scottish Water Energy Use

The high electricity consumption can be attributed to many aspects of the company, a large part owing to the energy intensive processes necessary to clean wastewater. However, in the water distribution networks a great deal of energy is lost in leakages due to high pressure, and over the past few years there has been an impetus to cut leakages in Scottish Water Pipe networks. One one way of doing so is to reduce the pressure in the system, which can be achieved by break pressure tanks, however such tanks require frequent water quality monitoring to comply with SEPA standards which require expenditure. These can be avoided by the use of pressure reduction valves which require less maintenance costs, however, the energy required to reduce pressure may be better put to use with the installation of small scale hydro which can accomplish the same objectives whilst providing a means of income by exporting electricity. At present there is no easy way of determining the potential power generation and cost savings in a water network from pressure reduction. Computer software ESP-r is an integrated energy modelling tool developed by the University of Strathclyde which can model mass flows (ESRU 2001). Therefore it is possible to create a mass flow network in ESP-r which can be run with the Mass Flow Solver which accompanies ESP-r, thus calculating the flow at each desired point in the network. A turbine may then be included in the network and ultimately the power available at that particular point can be determined knowing the required pressure drop, flow, and efficiency of the turbine. Thus, a financial analysis can be undertaken which considers the available tariffs, the cost of the turbine, maintenance costs, and grid connection. As the turbine is likely to be small scale between 10 and 100kw the feed in tariffs will alleviate the capital costs a great deal in the long term. Businesses can tend to be sceptical of investments with longer paybacks, however with the incentives introduced by the government added to the vast consumption of energy by water utilities themselves, they are more likely to consider such an undertaking, which gives the impetus to the development of water network energy capture modelling software.

Objectives, Scope, & Methodology

The primary objective of this thesis was to develop a software tool which can calculate the energy available from pressure loss in water networks. This was to be achieved using ESP-r to create a flow network with boundary conditions, nodes, and components to represent the characteristics of a network. Meetings were planned with Scottish Water to provide consultancy and information regarding the loch Turret network and flow data. A meeting was held with Ewan Band from Scottish Water to provide scope for potential sites which would be useful to base a preliminary model on. Three sites were singled out for their potential, within the Loch Turret main trunk network near Crieff, Perthshire, which supplies Crieff, and stretches south to Dunblane and East to Abernethy and West of Perth. The three sites of interest currently use break pressure tanks to reduce the pressure in the network to atmospheric pressure. However, these tanks require attention to maintain water quality levels, and replacing these with pressure reducing valves or turbines would reduce maintenance costs and generate an income. A cost analysis was then required to assess the feasibility of the proposals.

Further investigation included the effects of varying the pipe diameter and flow, and also the impact of temperature increase on the flow and ultimately the final payback. Plans to extend the Loch Turret network into Perth have been considered at Scottish Water as the existing pumping costs from the Tay could be reduced, and selecting the pipe diameter will affect the power available for capture from the turbines which generate power from flow. This was a problem to be modelled and assessed as further study by developing the models to account for increased flows and pipe extensions.

Literature Review

Water leakage is a problem all over the world with approximately 32 billion m3 of treated water escaping water networks globally (Kingdom et al.2006). Management of leakage has therefore become a priority for water utility companies to reduce energy wastage and cost. At Scottish Water energy is one of their biggest OpEx costs at currently c. £40 million per year (Scottish Water 2011).

A common and widely used method to reduce and control pressure in water distribution networks is through the use of Pressure Reducing Valves (PRV). They operate when the downstream pressure exceeds the specified limit, whereby a lock is activated which increases the head loss to reduce the pressure back to the desired level (Ramos et al. 2005). Research has shown that pressure control can be controlled well with components which induce a head loss such as PRVs or turbines (Kalanithy, 1998) (Martinez, 1999) (Reis, 1999) (Reis, 1997) (Ulanicka et al., 2001) (Araujo et al., 2003). Leakage can be reduced by introducing this method which prevents the pressure from rising to levels where rupture can occur. Micro hydro systems can provide a better alternative to PRVs as they control the pressure while generating power and income in an environmentally friendly way *(Ramos & Borga 2000a,b; Valadas & Ramos 2003*. The benefits of such a system include a constant assured source of power which can be fed into the grid without affecting the supply of water. Software packages exist which model the optimisation of pumps to save energy in water networks (S.Bunn, 2005), however, determining the feasibility of small scale hydro in water networks could be made simpler with a tool that calculates the power available from a network and the financial benefits of installing a small turbine or a pump as a turbine in such locations where the power and flow are too small for a normal turbine. The current market for small scale hydro can accommodate a range of flows and pressures, and an example of which has been successfully installed in another trunk network is the Difgen unit which can be attached to a PRV valve. Difgen Units are a patented design which combines pressure reduction with hydropower generation (Ørke, 2010). According to Zeroplex, it is a "Volumetric displacement turbine - a rotating barrier. A fixed volume is dosed through the turbine for each revolution; By applying load, rotational speed is retarded, and a differential pressure is created. Upstream/downstream pressure is dynamically controlled".

Model 1

Defining the Model

The operating system Linux was used in the form of Ubuntu 11.04 in order to run ESP-r smoothly with its mass flow solver component. An arbitrary model was selected and amended in ESP-r to provide the basis for the water network which was then saved as a new configuration file named Model 1. The network for the original file was based on a mass flow network for an office building, which was linked with zones in the building. This links were disregarded in the new file and an entirely new mass flow network was created by re-writing the .afn file in the networks folder. A screenshot in Figure 2 below shows the stage at with the network was modified in ESP-r:

```
 Nodes
   Name         |Fluid |    Type    |Height |  Data1 |   Data2
 a Inlet         water  bound fix P  300.00      0.0      0.0
 b 2             water  internal     237.70      0.0      0.1
 c 3             water  internal     207.00      0.0      0.1
 d 4             water  internal     146.00      0.0      0.1
 e 5             water  bound fix P   88.002079700.0      0.0
 f Aux_1         water  internal     270.00      0.0      0.0
 g Aux_1_Outlet  water  bound fix P  240.00 588600.0      0.0
 h Aux_2         water  bound fix P  170.001275300.0      1.0
 i Aux_3         water  bound fix P  100.001962000.0      1.0
   ------------------------
 + add/delete/copy node
 ? Help
 - Exit
```

Figure 2: Screenshot from ESP-r showing input of nodes and boundary conditions

The new network was based on a the loch Turret Reservoir near Crieff, Perthshire, Scotland based on information provided by Scottish Water. This included pipe diameters, lengths, site elevations, and locations of break pressure tanks, of which three in the network were singled out for their energy potential as they require PRV valves. A drawing of the break pressure chamber is shown in figure 1 below, which shows the extent of the area which can be used to house a turbine.

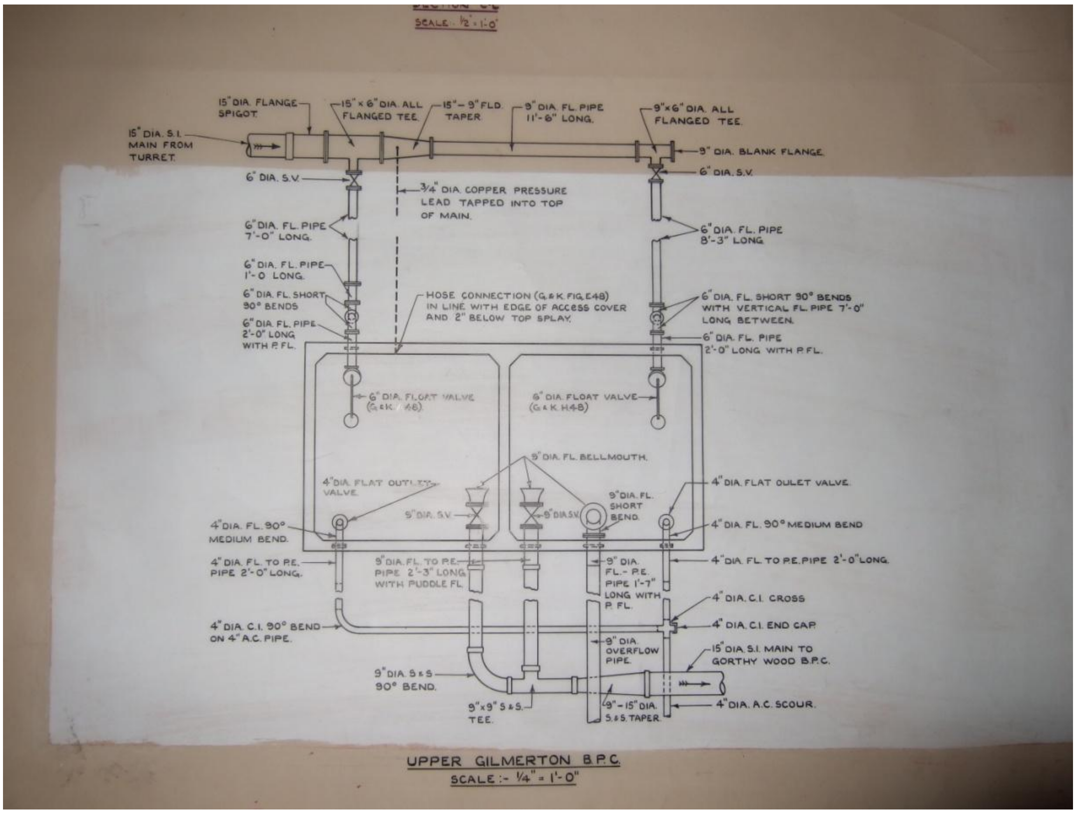
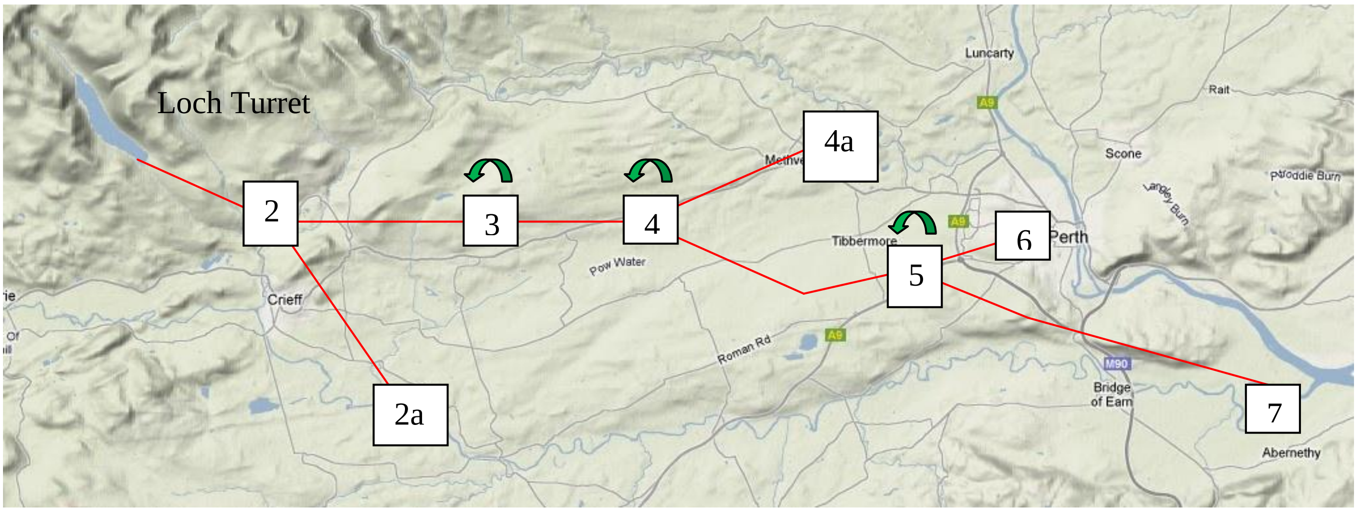


Figure 3: Drawing of Upper Gilmerton Break Pressure Tank (Scottish Water n.d.)

A map of the trunk main system is shown in Figure 4, and information regarding the locations of nodes is provided in Table 1.



Key: = Proposed site of turbine; = Pipe; = Node

Figure 4: Map of Scenario 1 based on the Loch Turret Distribution Network

Table 1: Node Data Input

Node *Description/Location*	**Height** *m*	**Pressure** *Pa*	**Node Volume** *m3*
1. Loch Turret	300	0	0
- Inlet	300	0	0
2. Turret East	280	0	0.11045
2a Braco	200	981000	0
3. Gilmoreton Upper	238	0	0.11045
- Turbine A	238	0	0.11045
4. Gorthy	207	0	0.11045
- Turbine B	207	0	0.11045
4a. Pitcairn	150	1471500	0
5. Crossgates	146	0	0.11045
- Turbine C	146	0	0.11045
6. Hillend	100	1962000	0
7. Abernethy	88	2079700	0

Boundary conditions were defined at the extents of the network based on the following assumptions:

- Boundary nodes are initially assigned pressures based on height difference from the reservoir.
- The roughness factor k was taken as 0.15mm in all pipes
- The average node temperature was 10^0 C
- Flow controlled at inlet (Loch Turret) based on yearly average of 7mL/d
- Pressure drops to zero in Break pressure tanks in the trunk main pipeline, therefore PRVs and Difgen units would achieve the same reduction

Esp-r features a selection of network flow components in its database of which only three were necessary to simulate a water network. A summary of the components are provided in Tables 2 and 3 below:

Table 2: Pipe Component Definition

Pipe Component Description	**Pipe** #	**Diameter** *m*	**Length** *m*
General flow conduit component (m=ρ.f(Cd,A,ρ,dP))	1_1	0.375	1700
	1a	0.215	2700
	1_2	0.375	5900
	2	0.375	1675
	2a	0.245	13975
	3a	0.375	5425
	3	0.375	3400
	4	0.230	17025

Table 3: Flow Control and Turbine definition

Ancillary Components	**Name**	**Flow** m^3/s	**Volume** m^3
Fixed flow rates controller	Flow_cntl	0.081	-
Common orifice flow component (m=ρ.f(Cd,A,ρ,dP))	Turbine_A	-	10
	Turbine_B	-	10
	Turbine_C	-	10

Pipes were sized based on the existing dimensions in the Loch Turret network, however, the network was simplified for demonstration purposes, therefore diameters of pipes 1a, 2a and 4 were amended to achieve the a flow similar to that which exists in the current system. It is possible for the Network to be more accurately represented given the full extent of the elevations, lengths, and flows of the entire network, nevertheless the purpose of this paper is to demonstrate the application of the energy calculation tool. The pipe component was selected as type 210 in esp-r which gives the following description:

"a general flow conduit component takes into account frictional and dynamic losses within a duct or pipe assuming the following:

- a uniform cross section
- no pressure gain from a pump or fan
- steady state conditions"

(ESRU 2001)

When selecting the attributes of the pipe flow conduit component it was necessary to define its hydraulic diameter, cross sectional area, length, absolute wall roughness (mm), and a sum of local dynamic loss factors which was taken as 1. Subsequently, a flow controller was used to replicate the average demand for the network which was 7ML/d from May 2011 to 2012. Moreover, in order to model the pressure drop which exists over the three break-pressure tanks in the system and which would ultimately represent the pressure drop from the proposed turbine, a common orifice flow component was introduced. This required a dimension input and a value of $10m^3$ was entered to ensure complete loss of pressure, however in reality the pressure drop would be required to remain above 0.3 bar to maintain adequate pressure in the network (Scottish Water, 2009).

Mass Flow Solver

The network flow file was then opened with the mass flow solver which calculated the mass flows and pressures in the whole network during a period of one month, which was the amount of time required for the iterative process to arrive at a solution. Figures below shows the mass flow solver during the iteration process and the results output in text editor *gedit* at the end of the iteration period respectively:

```
Date: 31/ 1/1967 24.000  Dryb=  6.6  Wdir= 255.  Wvel=  5.7   It=    1 OK=1.00
   Node       F T  Temperature    Height      Pressure     Residual      Sabs(Flw)
Flow_cntl     2 2   10.000       300.00       0.0000      -127.30       127.30
Inlet         2 0   10.000       300.00      0.45052E+06 -0.42633E-13   254.61
Aux_1         2 0   10.000       280.00      0.55993E+06  0.42633E-13   254.61
Aux_1_Outlet  2 2   10.000       200.00      0.98100E+06   47.307       47.307
2             2 0   10.000       237.70      0.85501E+06 -0.88200E-07   159.99
2+Turb        2 0   10.000       237.70      0.85501E+06 -0.32020E-07   159.99
3             2 0   10.000       207.00      0.11221E+07  0.32304E-06   159.99
3+Turb        2 0   10.000       207.00      0.11221E+07  0.79063E-04   159.99
Aux_2         2 2   10.000       150.00      0.14715E+07   22.119       22.119
4             2 0   10.000       146.00      0.16841E+07   1.0630       114.69
4+Turb        2 0   10.000       146.00      0.16841E+07  -1.0631       114.69
Aux_3         2 2   10.000       88.000      0.20797E+07   25.784       25.784
Extension     2 2   10.000       102.20      0.19620E+07   16.756       16.756
5             2 2   10.000       88.000      0.20797E+07   15.338       15.338
   From          To           Comp         Typ F      Pi-Pj        Pstack        Flow 1        Flow 2
Flow_cntl     Inlet         Flow_cntl     460 2 -0.45052E+06   0.0000        127.30        0.0000
Inlet         Aux_1         Pipe_1.1      210 2 -0.10941E+06  0.19618E+06    127.30        0.0000
Aux_1         Aux_1_Outlet  Aux_1_Pipe    210 2 -0.42107E+06  0.78474E+06    47.307        0.0000
Aux_1         2             Pipe_1.2      210 2 -0.29508E+06  0.41493E+06    79.997        0.0000
2             2+Turb        Turbine1       40 2  0.32000E-01   0.0000        79.997        0.0000
2+Turb        3             Pipe_2        210 2 -0.26712E+06  0.30114E+06    79.997        0.0000
3+Turb        4             Pipe_3        210 2 -0.56193E+06  0.59836E+06    57.878        0.0000
3+Turb        Aux_2         Aux_2_Pipe    210 2 -0.34938E+06  0.55913E+06    22.119        0.0000
3             3+Turb        Turbine_2      40 2  0.32000E-01   0.0000        79.997        0.0000
4             4+Turb        Turbine_3      40 2  0.16141E-01   0.0000        56.815        0.0000
4+Turb        Aux_3         Aux_3_Pipe3   210 2 -0.39564E+06  0.56893E+06    25.784        0.0000
4+Turb        Extension     Pipe_Ext      210 2 -0.27794E+06  0.42964E+06    16.756        0.0000
4+Turb        5             Pipe_4        210 2 -0.39564E+06  0.56893E+06    15.338        0.0000
```

Figure 5: Screenshot of Results from Mass Flow Solver

The Table 4 below shows the results of the solver whereby the pressure is shown over the length of each component. For example, the pressure drop at the site of Gilmerton Upper is the sum of the pressures leading up to that point in the network, which will be equal to the pressure increase from the nodes 'Ínlet' to 'Turret East' and 'Turret East' to 'Gilmerton Upper', which is 6.11 bar (1.96 + 4.15). The flow results were similar to the levels recorded in the information provided by Scottish Water, which is based on averages for the year of 2009/10.

Table 4: Comparison of Mass Flow Results for Model 1 and Real Values

Mass Flow Results for Model 1					
From	**To**	**Component**	**Pressure Stack (Bar)**	**Flow (l/s)**	**Actual (l/s)**
1. Loch Turret	- Inlet	Flow_cntl	0.00	81.014	80.184
- Inlet	2. Turret East	Pipe_1.1	1.96	81.014	80.184
2. Turret East	2a Braco	Aux_1_Pipe	7.85	32.614	32.642
2. Turret East	3. Gilmoreton Upper	Pipe_1.2	4.15	48.399	47.542
3. Gilmoreton Upper	- Turbine A	Turbine A	0.00	48.399	47.542
- Turbine A	4. Gorthy	Pipe_2	3.01	48.399	47.542
4. Gorthy	- Turbine B	Turbine B	0.00	48.399	47.292
- Turbine B	4a. Pitcairn	Aux_2_Pipe	5.59	16.418	17.755
- Turbine B	5. Crossgates	Pipe_3	5.98	31.982	29.537
5. Crossgates	- Turbine C	Turbine C	0.00	31.967	29.537
- Turbine C	6. Hillend	Aux_3_Pipe3	4.51	20.084	14.49
- Turbine C	7. Abernethy	Pipe_4	5.69	11.898	15.05

A spreadsheet was created in excel to derive the energy available at the break pressure tanks where the pressure is reduced to zero, and to explore power generation and a cost analysis of a micro turbine or difgen unit.

The power available to the DIFGEN units was calculated using the required pressure head differential across the PRV, at three locations in the water network where break water tanks exist, using $P = \eta\rho ghQ$, where η is a variable efficiency, ρ is the density of freshwater (1000kg/m^3), h is the head loss over the Difgen unit in metres, and Q is the flow rate (m^3/s) at the location in question, calculated with the mass flow solver. The efficiency was provided by Difgen for a flow of 54l/s and pressure differential of 6 bar as 0.65, whereby the outlet pressure is left at 0.4 bar to maintain sufficient pressure in the pipeline.

Table 5 displays the annual power generated by Difgen units replacing three break water pressure tanks in the Loch Turret network.

Table 5: Annual Power Production for Scenario 1

Annual Power Production								
Scenario	**Location**	**Pressure Differential**	**Flow**	**Head**	**Power Available**	**Power Generated**		**Combined**
#		*Pa*	*m3/s*	*m*	*kw*	*kw*	*kWh*	*MWh*
1	Gilmerton U	571120	0.0484	58.2	27.6	18.0	157,391	**331**
	Gorthy	261140	0.0484	26.6	12.6	8.2	71,966	
	Crossgates	558360	0.0320	56.9	17.8	11.6	101,633	

The Difgen Units are approximately 65% efficient at this flow rate and pressure differential according to Zeroplex, and complete dissipation of pressure is unachievable, reaching a pressure of 0.4 bar. Without access to an efficiency curve for the unit in question it is difficult to expand the program to accommodate fluctuations in power generation, therefore this aspect would require further investigation. The same can be said of the pump as a turbine, however efficiencies have been shown to reach up to 85% (Ramos et al. 2005). The maximum power available based on the average flow is 27.6kw at the highest location of Gilmerton Upper, which is reduced to 18kw due to the efficiency of the turbine, which, assuming is in operation all year round yields an output of 157,391kWh. The pressure head available at Gorthy is less than half of that available at Gilmerton Upper and Crossgates, and as such yields less than half the power available at Gilmerton Upper despite having the same flow level, which can be observed well in Figure 6. Thus the power generation from a Difgen unit is reliant upon a combination of flow and pressure.

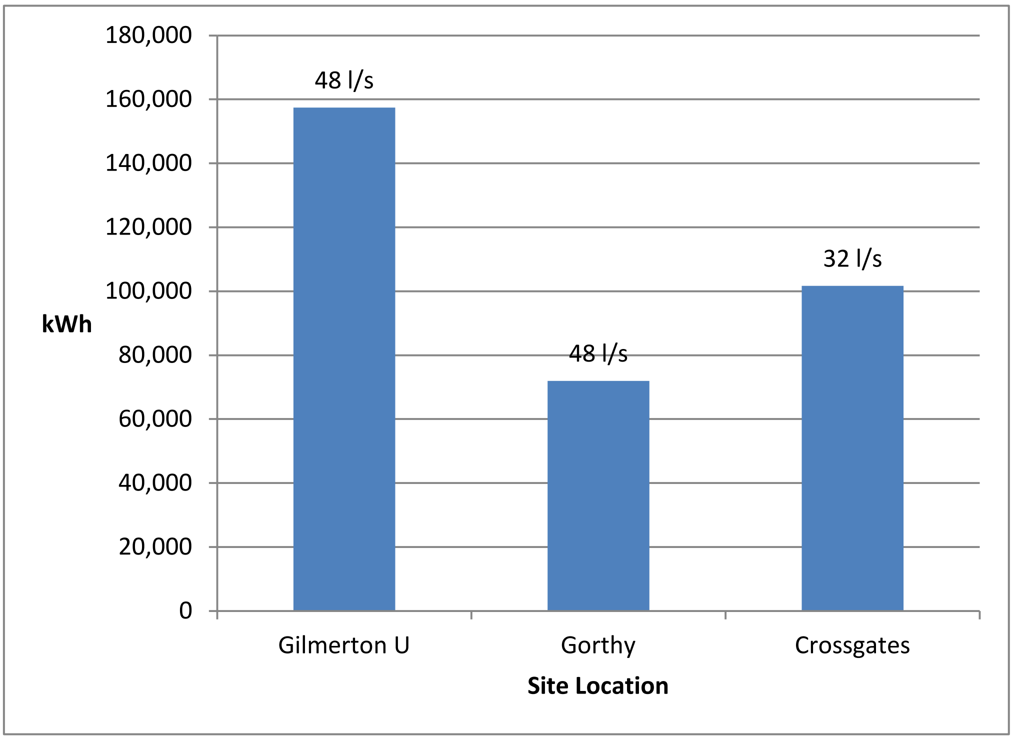


Figure 6: Annual Power Generation for Scenario 1 based on site location

Model 2

The existing water supply for Perth is pumped from the river Tay, which is an energy intensive process, and which could be alleviated somewhat by joining the network with the Loch Turret trunk main. Due to problems with insufficient pipe sizes and adaptability in the western section of the Loch Turret network there is more water available than can be used. Therefore the potential exists for an increase in supply from the current average by up to 4ML/day to deliver to one of two water storage reservoirs in Perth. Linking the networks would require a pipe extension from Crossgates to Burghmuir via a 6km pipe, and the diameter of the pipe may be selected based on the energy available to capture at the PRV valves. It was decided therefore to investigate the degree of variation in energy available by selecting pipe diameters from 200 to 350mm to represent the potential network expansion. A pipe of 6006m in length was introduced, with boundary pressure equal to the elevation of the current site at Burghmuir at 100m AOD, and the flow controller at loch turret was increased by 4ML/day. Table 6 below shows the variation in velocity in each pipe; Scottish Water specify that 0.5m/s should be the target design velocity, and should not exceed 1.0m/s, therefore a 350mm pipe can be disregarded as it falls below 0.5m/s. Diameters at the smaller end cause other problems such as friction loss which may allow the hydraulic energy line to fall depending on the topography of the land, and this value is required to be maintained at 3m above the ground (Scottish Water 2009).

Table 6: Variation of Velocity and flow from according to pipe diameter

Diameter *mm*	**Flow** *m3/s*	**Velocity** *m/s*
200	0.016756	0.53
250	0.02592	0.53
300	0.034686	0.49
350	0.042024	0.44

A comparison of the results can be seen in Table 7 below, where the impact of this expansion on the power available was clearly visible. The flow rate increases considerably with the addition of the new network from 48.4l/s originally at Gilmerton Upper to 80l/s and upwards. When this happens the Difgen Units increase their output from 331 MWh annually to 560 MWh and greater. This will have a large impact on the annual revenue and the viability of the project, which will be discussed in the cost analysis.

Table 7: Annual Power Generation from Scenarios 1 & 2

Annual Power Production							
Scenario	**Pipe Extension Diameter**	**Location**	**Pressure Differential**	**Flow**	**Power**		**Combined**
#	*mm*		*Pa*	*m3/s*	*kw*	*kWh*	*MWh*
1	-	Gilmerton U	571120	0.0484	18.0	157,391	**331**
		Gorthy	261140	0.0484	8.2	71,966	
		Crossgates	558360	0.0320	11.6	101,633	
2	200	Gilmerton U	571120	0.0800	29.7	259,994	**560**
		Gorthy	261140	0.0800	13.6	118,947	
		Crossgates	558360	0.0568	20.6	180,632	
	250	Gilmerton U	571120	0.0819	30.4	266,342	**584**
		Gorthy	261140	0.0819	13.9	121,783	
		Crossgates	558360	0.0616	22.4	195,979	
	300	Gilmerton U	571120	0.0836	31.0	271,743	**604**
		Gorthy	261140	0.0836	14.2	124,252	
		Crossgates	558360	0.0653	23.7	207,621	

The results shows there is a small difference in the annual power yield between diameter sizes of 200, 250 and 300mm. The friction loss in the 200mm is higher, which may require a more accurate study of the ground to assess the possibility of the hydraulic energy line falling below 3m. A comparison of the power generation from the existing network versus that from the extension using a 250mm pipe can be observed in Figure 7.

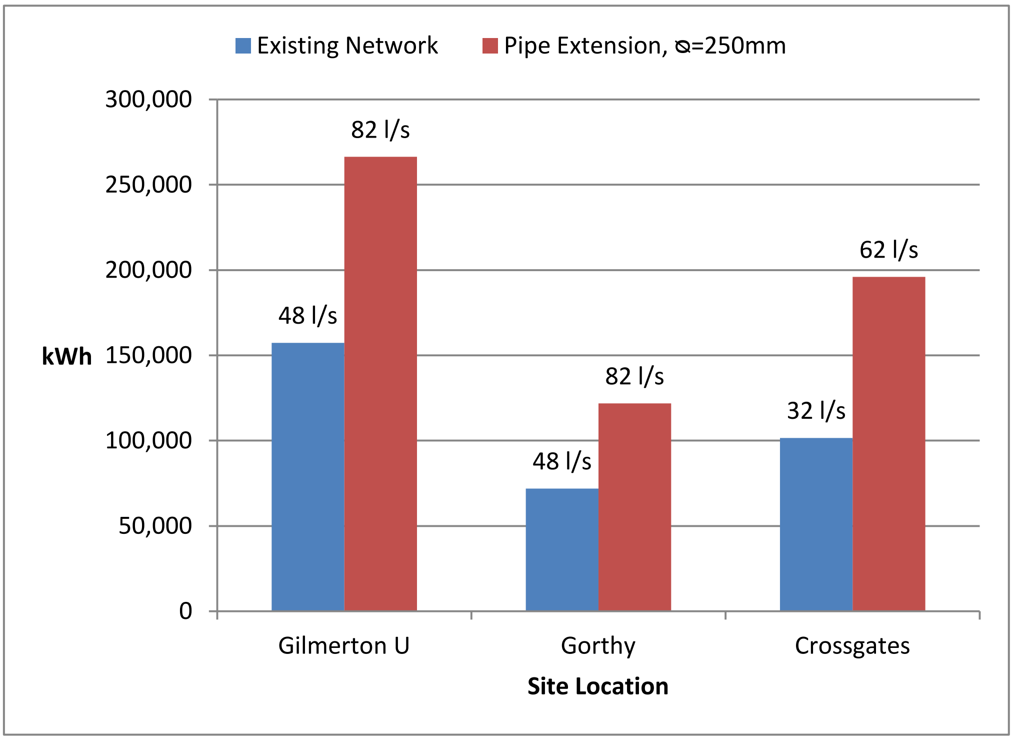


Figure 7: Annual Power Production from Scenarios 1 & 2

The difference in diameter chosen has an influence on the power generation of the Difgen unit and thus the payback of the project. It is important then to consider the cost savings of a variety of scenarios for the water company to determine the best possible plan.

Temperature and Climate

Trends in inland water temperatures in Scotland are showing an increase[(SEPA, 2010)]. The average temperature varies annually from 9.6 to 10 degrees Celsius in Perthshire, based on data from 2009. The first model was investigated by varying the water temperature from 8 to 12 degrees Celsius to determine the impact on the flow rate and power generation. This was achieved by varying the temperature of each node individually, and the variation in flow can be seen in Figure 8 below. It is apparent that there is little change in flow between 8 and 12 degrees Celsius, whereby the flow does decrease as the node temperature approaches 12 degrees Celsius.

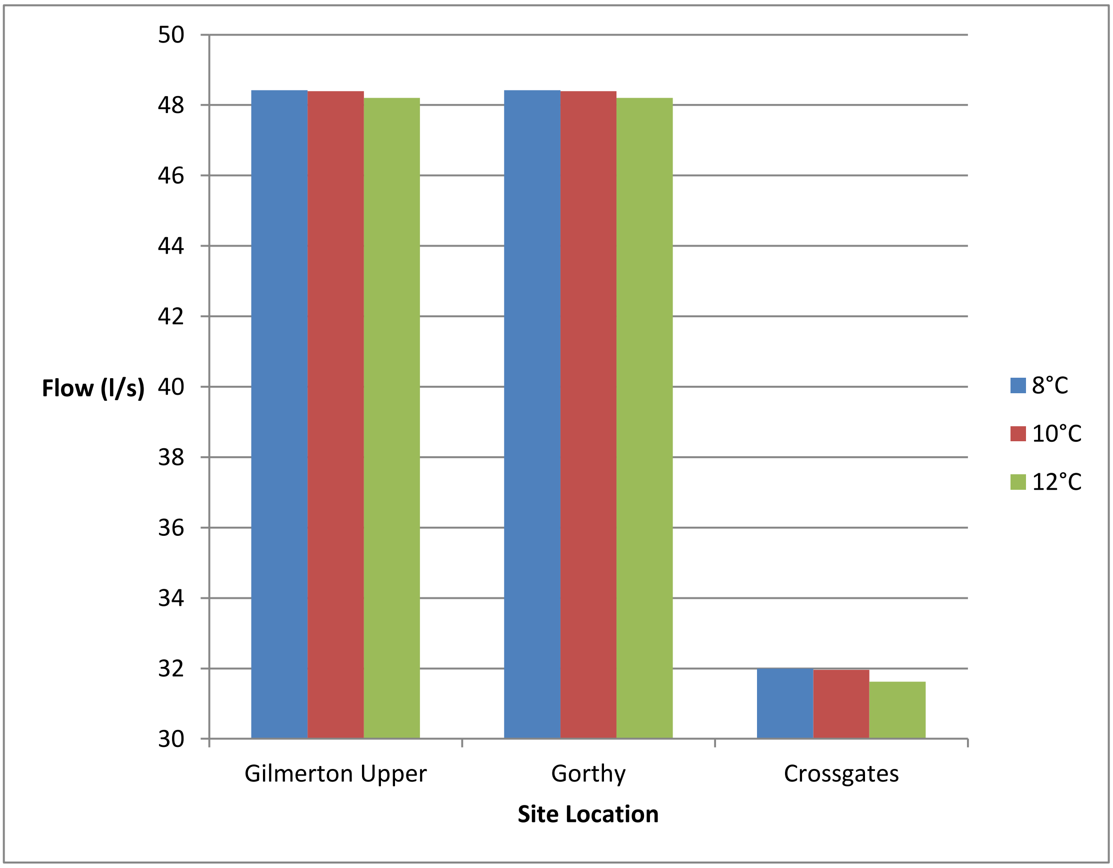


Figure 8: Variation in Power Generation from Temperature change at Turbine location

Financial Analysis

The Tariff plan used applies to hydro generating stations with installed capacities of 100kw or less (Ofgem 2012), A summary is shown below:

Table 8: FITs for Hydro Power (Ofgem 2012)

Lower limit	Upper Limit	Generation Tariff	Fixed Export	Total Tariff
kW	*kW*	*£/kWh*	*£*	*£/kWh*
0	15	0.207	0.032	0.239
15	100	0.198	0.032	0.230

The total power available to the sites in question only falls below 15kW once, in scenario 1 at Gorthy, so the tariff used for the rest of the sites is 19.8 pence/kW. The fixed export tariff was taken as £0.032, according to Ofgem. The cost of a Difgen unit can be rounded up to £200,000, therefore considering the inclusion of all three sites the sum total of installation has been approximated to £600,000. A simple breakdown of the costs for one Difgen unit is shown in Table 9 which includes costs provided by Zeroplex. An important aspect to consider is the connectivity to the grid, which may prove to be a critical part of the cost analysis due to the rural locations of the turbines. It was unclear whether Civil works and electrical installation or grid connectivity had been accounted for in the cost breakdown offered by Difgen, therefore estimations have been included in the financial analysis, which is shown in Table 10.

Table 9: Equipment cost assumptions

Equipment Cost	
	£
Equipment*	125000
Other*	75000
Civil Works	4000
Electrical Installation	16,000
Total	**220,000**

*Costs given by Zeroplex

Table 10: Financial Analysis for Difgen Units in Scenarios 1 & 2

Option	**Pipe Extension Diameter** *mm*	**Total Tarriff** *p/kWh*	**Annual Savings** *£*	**Equipment** *£*	**Annual Maintenance** *£*	**Payback** *Years*	**Cost** *p/kWh*	**IRR** *%*	**NPV** *£*
1	-	0.228	35,885	216000	2100	9.1	11.7	-2%	-£1,041
		0.251	18,063	216000	2100				
		0.228	23,172	216000	2100				
			77,121	648000	6300				
2	200	0.228	59,279	216000	2100	5.3	6.9	12%	£7,617
		0.228	27,120	216000	2100				
		0.228	41,184	216000	2100				
			127,583	648000	6300				
	250	0.228	60,726	216000	2100	5.1	6.6	13%	£8,431
		0.228	27,766	216000	2100				
		0.228	44,683	216000	2100				
			133,175	648000	6300				
	300	0.228	61,957	216000	2100	4.9	6.4	13%	£9,079
		0.228	28,330	216000	2100				
		0.228	47,338	216000	2100				
			137,625	648000	6300				

Analysis of both scenarios shows a marked improvement in the payback time and cost in p/kWh. In the original scenario it would take almost eight years to break even, whereas Scenario 2 reduces this to around 5 years depending on the choice of pipe diameter, and the price per kWh shows a similar trend decreasing from 11.7p/kWh to 6.9p/kWh and less. The Internal rate of return for the existing scenario is low at 2%, with a negative net present value in the first ten years. Scenario 2 however shows a much more attractive IRR of 11% and £7617 in net present value increasing to 13% and £9079 respectively for the largest considered pipe diameter of 300mm. Full details of the financial analyses can be found in the appendices. The financial analysis includes inflation at a rate of 1% per annum, over a period of 20 years which is based on the life expectancy (Zeroplex 2010). It is clear that the increase in flow has a strong impact on the payback years for the proposals. Varying the diameter has less of an impact, however the difference in NPV and IRR is there. Ultimately, the decision on the pipe diameter will depend on the future demand and whether even more expansion will be possible, however the increase in revenue from the difgen units is visible and should not be ignored.

If the capacity of the micro turbines was capped at 15kw then the payback for Scenario 1 would change very little, if the cost of the equipment was left unchanged, due to the increase in tariff at the point of 15kw capacity, as shown in Table 11.

Table 11: Financial Analysis for Scenario 1 based on 15kw Capacity limit

Option	**Difgen Units** **Total Tarriff**	**Annual Savings**	**Equipment**	**Annual Maintenance**	**Payback**	**Cost**
	p/kWh	*£*	*£*	*£*	*Years*	*p/kWh*
1	0.251	21,438	216000	2100	11.9	15.9
	0.251	18,063	216000	2100		
	0.251	21,438	216000	2100		
		60,939	648000	6300		

Sensitivity Analysis

Turbine Efficiency

In order to understand the impact of the turbine efficiency a sensitivity analysis was carried out whereby the efficiency was varied by 10%. Figure below displays the impact of this variation on the two considered Scenarios, whereby the difference is clearer to see in Scenario 2. On closer inspection of the figures (See Table in Appendices) the variation in power generation due to efficiency is greatest between the 300mm diameter pipe for Scenario 2, with a difference of 120,723kWh, whereas the same 10 % variation in efficiency produces a smaller difference in Scenario 1 of 66,198kWh. However, this bears little importance due to the difference in overall output, as the expanded network clearly yields a far greater power generation, as seen in Figure 10 below.

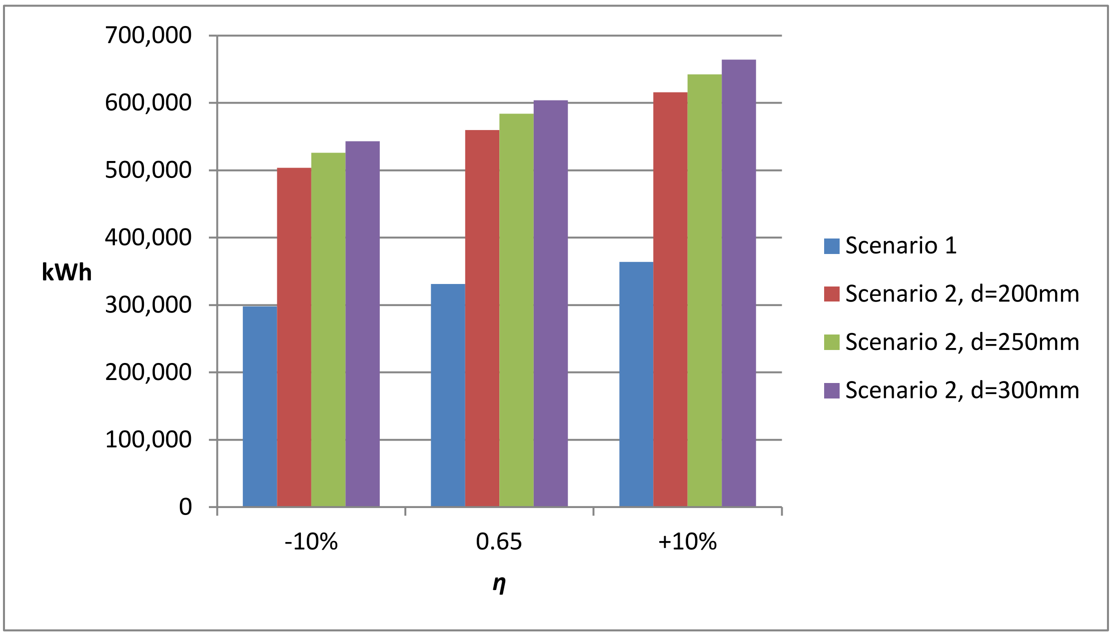


Figure 9: Variation in Power Generation with efficiency in Scenarios 1 & 2

The impact of this financially are shown in Table 12 below. It can be said from inspection of the Net Present Value that the first Scenario is highly sensitive to a change in efficiency, having a negative value for the current estimated efficiency and less. Moreover the internal rate of return turns positive only after ten years which is undesirable from a business perspective. The respective values for Scenario 2 however are shown to be less affected by the variation in efficiency, giving a more robust outlook for the project.

Table 12: Sensitivity of Turbine Efficiency in Financial Analysis

Option	**Pipe Extension Diameter**	**Turbine Efficiency, η**	**Difgen Units Payback**	**Cost**	**IRR**	**NPV**
	mm	*0.65*	*Years*	*p/kWh*		
1	-	-10%	10.3	13.0	10%	-£2,140
		0.65	9.1	11.7	12%	-£1,041
		+10%	8.3	10.6	14%	£57
2	200	-10%	6	7.7	22%	£5,670
		0.65	5.3	6.9	25%	£7,617
		+10%	4.8	6.3	28%	£9,474
	250	-10%	5.7	7.4	23%	£6,493
		0.65	5.1	6.6	26%	£8,431
		+10%	4.6	6.0	30%	£10,369
	300	-10%	5.5	7.1	24%	£7,076
		0.65	4.9	6.4	28%	£9,079
		+10%	4.5	5.8	31%	£11,082

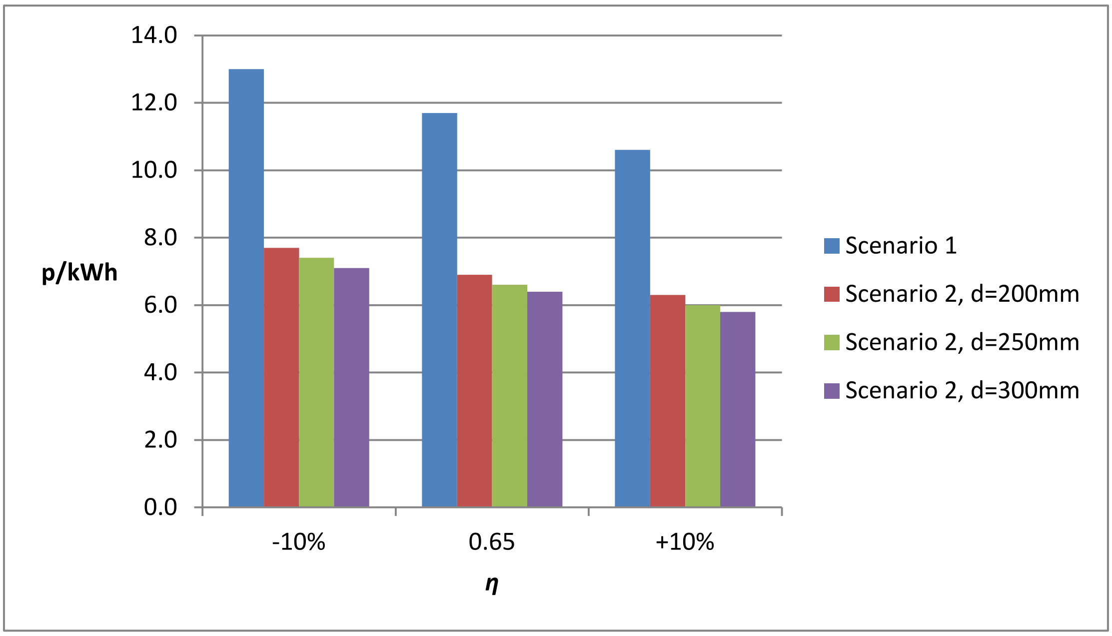


Figure 10: Variation of Cost with turbine efficiency

Figure 11 shows the difference in cost in pence/kWh. It is clear that Scenario 1 is affected the most by changes in the overall efficiency of the turbine, whereby the cost varies by a magnitude of 2.4p/kWh. In contrast, Scenario 2 with a choice of 300mm varies the least by 1p/kWh, and it is generally clear from the graph that Scenario 2 is far less affected by the change in efficiency. This suggests that the extension of the loch Turret network into Perth would be more beneficial as a higher flow would on average generate more income despite a small change in efficiency of the turbines.

Conclusions

The computer modelling software ESP-r was used to develop a model which represents a water network in Perthshire with the aim of calculating the mass flow through key locations in the network where the addition of a turbine could act as a pressure reducing valve. Flow results were used to calculate the power from a Difgen unit and a pump as a turbine, in order to determine the cost of such an undertaking. It was found that replacing break pressure tanks with Difgen units would generate approximately 331MWh annually assuming an efficiency of 60%. With the expansion of the network the available power could be increased nearly twofold assuming a pipe size of 300mm diameter. For the existing scenario the cost of procurement and installation would be unattractive in the short term having a negative NPV. However in the second scenario the NPV could be improved with a payback of under 5 years adhering to the current tariff system. This should give water utilities the incentive to develop their networks to capture the energy lost in pressure loss components, and furthermore give impetus to develop software to model networks and which could be used to calculate the energy and cost savings available in any network. Pumping water from the river Tay is an expensive exercise, therefore those costs could be considerably reduced with the extension of the Loch Turret network and construction of small scale Hydro in place of the break pressure tanks. A sensitivity analysis of the turbine efficiency showed that the first scenario could be subject to greater monetary losses in the event of an underperforming turbine. In the expanded network with increased flow however, the variation in efficiency would not pose such a threat to the financial viability of the proposals.

Further Study

Due to time restrictions, there were a number of aspects which need to be addressed for the development of this tool:

- The mass flow solver could be modified to calculate the total energy available across a turbine by inserting a formula in the program source code at the point where the pressure is dissipated over the common orifice component.
- Turbine efficiency curves were difficult to find, as manufacturers tend not to divulge such information readily. Efficiencies were given for one of the sites by Zeroplex, however each site has different attributes in terms of flow and pressure losses, therefore to improve accuracy and diversity for other networks the software may be developed to include this information.
- Other sites exist in Perthshire for the potential capture of pressure using small scale hydro however data such as site locations and flow rates were out of reach for this study.
- Due to the rural locations of the sites the connection to the grid is yet to be understood and costs have been estimated for the construction of the necessary infrastructure however this may prove to be prohibitive and a more detailed study will be necessary.

Appendices

Appendix A: Mass Flow Solver

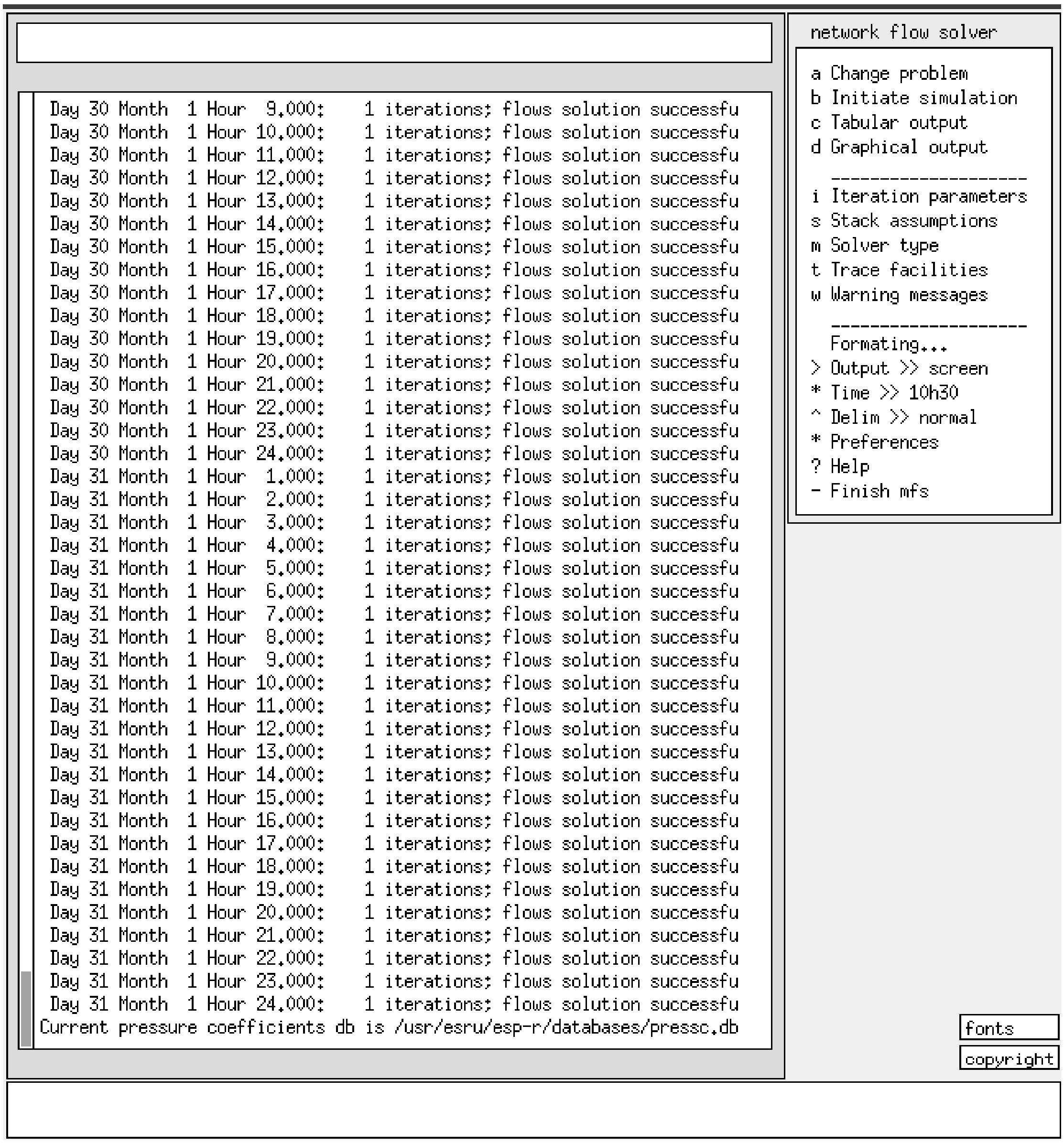


Figure 11: Screenshot of Mass Flow Solver during iteration process

Appendix B: Friction Loss in Pipe Extension

Table 13: Friction Loss Calculations for Pipe Extension

Diameter	**Flow**	**Velocity**	**Friction Loss**
mm	*m3/s*	*m/s*	*m*
200	0.016756	0.53	9.4
250	0.025920	0.53	6.8
300	0.034686	0.49	4.6
350	0.042024	0.44	3.0

The friction loss was calculated using the formula:

$$h_f = \left(\frac{QC_c}{zD^{\frac{8}{3}}}\right)L$$

Appendix C: Financial Analysis

Table 14: Financial Analysis of Scenario 1

Scenario 1										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**£**	**%**	**%**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	331,000	19.80	3.20	£76,130.00	2100.00	-£573,970.00	-£573,970.00	1	-	-
2013	331000	20.00	3.23	£76,891.30	2184.00	£74,707.30	-£499,262.70	2	-	-£1,041.20
2014	331000	20.20	3.26	£77,660.21	2271.36	£75,388.85	-£423,873.85	3	-	-£943.84
2015	331000	20.40	3.30	£78,436.82	2362.21	£76,074.60	-£347,799.25	4	-	-£845.87
2016	331000	20.60	3.33	£79,221.18	2456.70	£76,764.48	-£271,034.77	5	-21%	-£747.32
2017	331000	20.81	3.36	£80,013.40	2554.97	£77,458.42	-£193,576.34	6	-12%	-£648.18
2018	331000	21.02	3.40	£80,813.53	2657.17	£78,156.36	-£115,419.98	7	-6%	-£548.48
2019	331000	21.23	3.43	£81,621.66	2763.46	£78,858.21	-£36,561.78	8	-2%	-£448.22
2020	331000	21.44	3.47	£82,437.88	2874.00	£79,563.89	£43,002.11	9	2%	-£347.40
2021	331000	21.65	3.50	£83,262.26	2988.95	£80,273.31	£123,275.42	10	4%	-£246.06
2022	331000	21.87	3.53	£84,094.88	3108.51	£80,986.37	£204,261.79	11	6%	-£144.19
2022	331000	22.09	3.57	£84,935.83	3232.85	£81,702.98	£285,964.76	12	7%	-£41.82
2022	331000	22.31	3.61	£85,785.19	3362.17	£82,423.02	£368,387.78	13	8%	£61.04
2022	331000	22.53	3.64	£86,643.04	3496.65	£83,146.39	£451,534.17	14	9%	£164.38
2022	331000	22.76	3.68	£87,509.47	3636.52	£83,872.95	£535,407.12	15	10%	£268.18
2022	331000	22.99	3.72	£88,384.57	3781.98	£84,602.59	£620,009.71	16	11%	£372.41
2022	331000	23.22	3.75	£89,268.41	3933.26	£85,335.15	£705,344.86	17	11%	£477.06
2022	331000	23.45	3.79	£90,161.10	4090.59	£86,070.51	£791,415.37	18	12%	£582.11
2022	331000	23.68	3.83	£91,062.71	4254.21	£86,808.49	£878,223.86	19	12%	£687.54
2022	331000	23.92	3.87	£91,973.33	4424.38	£87,548.95	£965,772.81	20	12%	£793.32

Table 15: Financial Analysis of Scenario 2, with pipe diameter of 200mm

Scenario 2, 200mm pipe										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	559,573	19.80	3.20	£128,701.81	2100.00	-£521,398.19	-£521,398.19	1	-	-
2013	559,573	20.00	3.23	£129,988.83	2184.00	£127,804.83	-£393,593.37	2	11%	£7,617.05
2014	559,573	20.20	3.26	£131,288.71	2271.36	£129,017.35	-£264,576.01	3	11%	£7,790.27
2015	559,573	20.40	3.30	£132,601.60	2362.21	£130,239.39	-£134,336.63	4	12%	£7,964.85
2016	559,573	20.60	3.33	£133,927.62	2456.70	£131,470.91	-£2,865.71	5	12%	£8,140.78
2017	559,573	20.81	3.36	£135,266.89	2554.97	£132,711.92	£129,846.21	6	12%	£8,318.07
2018	559,573	21.02	3.40	£136,619.56	2657.17	£133,962.39	£263,808.60	7	12%	£8,496.71
2019	559,573	21.23	3.43	£137,985.76	2763.46	£135,222.30	£399,030.90	8	12%	£8,676.69
2020	559,573	21.44	3.47	£139,365.62	2874.00	£136,491.62	£535,522.52	9	12%	£8,858.02
2021	559,573	21.65	3.50	£140,759.27	2988.95	£137,770.32	£673,292.84	10	13%	£9,040.69
2022	559,573	21.87	3.53	£142,166.86	3108.51	£139,058.35	£812,351.19	11	13%	£9,224.70
2022	559,573	22.09	3.57	£143,588.53	3232.85	£140,355.68	£952,706.87	12	13%	£9,410.03
2022	559,573	22.31	3.61	£145,024.42	3362.17	£141,662.25	£1,094,369.12	13	13%	£9,596.68
2022	559,573	22.53	3.64	£146,474.66	3496.65	£142,978.01	£1,237,347.13	14	13%	£9,784.65
2022	559,573	22.76	3.68	£147,939.41	3636.52	£144,302.89	£1,381,650.02	15	13%	£9,973.92
2022	559,573	22.99	3.72	£149,418.80	3781.98	£145,636.82	£1,527,286.84	16	13%	£10,164.48
2022	559,573	23.22	3.75	£150,912.99	3933.26	£146,979.73	£1,674,266.57	17	13%	£10,356.32
2022	559,573	23.45	3.79	£152,422.12	4090.59	£148,331.53	£1,822,598.10	18	13%	£10,549.44
2022	559,573	23.68	3.83	£153,946.34	4254.21	£149,692.13	£1,972,290.23	19	13%	£10,743.81
2022	559,573	23.92	3.87	£155,485.81	4424.38	£151,061.42	£2,123,351.65	20	13%	£10,939.42

Table 16: Financial Analysis of Scenario 2, with pipe diameter of 250mm

Scenario 2, 250mm										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	584,103	19.80	3.20	£134,343.68	2100.00	-£515,756.32	-£515,756.32	1	-	-
2013	584,103	20.00	3.23	£135,687.12	2184.00	£133,503.12	-£382,253.20	2	13%	£8,431.09
2014	584,103	20.20	3.26	£137,043.99	2271.36	£134,772.63	-£247,480.57	3	13%	£8,612.45
2015	584,103	20.40	3.30	£138,414.43	2362.21	£136,052.22	-£111,428.35	4	13%	£8,795.25
2016	584,103	20.60	3.33	£139,798.57	2456.70	£137,341.87	£25,913.52	5	13%	£8,979.49
2017	584,103	20.81	3.36	£141,196.56	2554.97	£138,641.59	£164,555.11	6	13%	£9,165.16
2018	584,103	21.02	3.40	£142,608.53	2657.17	£139,951.36	£304,506.46	7	13%	£9,352.27
2019	584,103	21.23	3.43	£144,034.61	2763.46	£141,271.15	£445,777.62	8	13%	£9,540.81
2020	584,103	21.44	3.47	£145,474.96	2874.00	£142,600.96	£588,378.58	9	13%	£9,730.79
2021	584,103	21.65	3.50	£146,929.71	2988.95	£143,940.75	£732,319.33	10	13%	£9,922.19
2022	584,103	21.87	3.53	£148,399.00	3108.51	£145,290.49	£877,609.82	11	13%	£10,115.00
2022	584,103	22.09	3.57	£149,882.99	3232.85	£146,650.14	£1,024,259.96	12	13%	£10,309.24
2022	584,103	22.31	3.61	£151,381.82	3362.17	£148,019.66	£1,172,279.62	13	13%	£10,504.89
2022	584,103	22.53	3.64	£152,895.64	3496.65	£149,398.99	£1,321,678.60	14	13%	£10,701.93
2022	584,103	22.76	3.68	£154,424.60	3636.52	£150,788.08	£1,472,466.68	15	13%	£10,900.37
2022	584,103	22.99	3.72	£155,968.84	3781.98	£152,186.86	£1,624,653.54	16	13%	£11,100.20
2022	584,103	23.22	3.75	£157,528.53	3933.26	£153,595.27	£1,778,248.82	17	13%	£11,301.40
2022	584,103	23.45	3.79	£159,103.82	4090.59	£155,013.23	£1,933,262.04	18	13%	£11,503.97
2022	584,103	23.68	3.83	£160,694.86	4254.21	£156,440.64	£2,089,702.68	19	13%	£11,707.88
2022	584,103	23.92	3.87	£162,301.80	4424.38	£157,877.42	£2,247,580.10	20	13%	£11,913.14

Table 17: Financial Analysis of Scenario 2, with pipe diameter of 300mm

Scenario 2, 300mm pipe extension										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	603,617	19.80	3.20	£138,831.88	2100.00	-£511,268.12	-£511,268.12	1	-	-
2013	603,617	20.00	3.23	£140,220.20	2184.00	£138,036.20	-£373,231.92	2	13%	£9,078.68
2014	603,617	20.20	3.26	£141,622.40	2271.36	£139,351.04	-£233,880.89	3	13%	£9,266.51
2015	603,617	20.40	3.30	£143,038.62	2362.21	£140,676.41	-£93,204.48	4	13%	£9,455.85
2016	603,617	20.60	3.33	£144,469.01	2456.70	£142,012.31	£48,807.83	5	13%	£9,646.69
2017	603,617	20.81	3.36	£145,913.70	2554.97	£143,358.73	£192,166.56	6	13%	£9,839.04
2018	603,617	21.02	3.40	£147,372.84	2657.17	£144,715.67	£336,882.22	7	13%	£10,032.89
2019	603,617	21.23	3.43	£148,846.56	2763.46	£146,083.11	£482,965.33	8	13%	£10,228.24
2020	603,617	21.44	3.47	£150,335.03	2874.00	£147,461.04	£630,426.37	9	13%	£10,425.08
2021	603,617	21.65	3.50	£151,838.38	2988.95	£148,849.43	£779,275.79	10	13%	£10,623.42
2022	603,617	21.87	3.53	£153,356.76	3108.51	£150,248.25	£929,524.04	11	13%	£10,823.26
2022	603,617	22.09	3.57	£154,890.33	3232.85	£151,657.48	£1,081,181.52	12	13%	£11,024.57
2022	603,617	22.31	3.61	£156,439.24	3362.17	£153,077.07	£1,234,258.59	13	13%	£11,227.37
2022	603,617	22.53	3.64	£158,003.63	3496.65	£154,506.97	£1,388,765.56	14	13%	£11,431.65
2022	603,617	22.76	3.68	£159,583.66	3636.52	£155,947.14	£1,544,712.71	15	13%	£11,637.38
2022	603,617	22.99	3.72	£161,179.50	3781.98	£157,397.52	£1,702,110.23	16	13%	£11,844.58
2022	603,617	23.22	3.75	£162,791.30	3933.26	£158,858.04	£1,860,968.26	17	13%	£12,053.23
2022	603,617	23.45	3.79	£164,419.21	4090.59	£160,328.62	£2,021,296.88	18	13%	£12,263.31
2022	603,617	23.68	3.83	£166,063.40	4254.21	£161,809.19	£2,183,106.07	19	13%	£12,474.82
2022	603,617	23.92	3.87	£167,724.03	4424.38	£163,299.65	£2,346,405.72	20	13%	£12,687.74

Appendix D: Sensitivity Analysis

Table 18: Sensitivity Analysis of Turbine efficiency on Power Generation

Option	Pipe Extension Diameter	Turbine Efficiency, η	Annual Power Generation	Magnitude of Variation
	mm	*0.65*	*kWh*	*kWh*
1	-	-10%	297,891	66,198
		0.65	330,990	
		+10%	364,089	
2	200	-10%	503,616	111,915
		0.65	559,573	
		+10%	615,530	
	250	-10%	525,693	116,821
		0.65	584,103	
		+10%	642,513	
	300	-10%	543,255	120,723
		0.65	603,617	
		+10%	663,979	

Table 19: Financial Analysis for Scenario 1, turbine efficiency reduced by 10%

Scenario 1										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**£**	**%**	**%**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	364,089	19.80	3.20	£83,740.52	2100.00	-£566,359.48	-£566,359.48	1	-	-
2013	364,089	20.00	3.23	£84,577.93	2184.00	£82,393.93	-£483,965.55	2	-	£56.89
2014	364,089	20.20	3.26	£85,423.71	2271.36	£83,152.35	-£400,813.21	3	-	£165.23
2015	364,089	20.40	3.30	£86,277.94	2362.21	£83,915.73	-£316,897.48	4	-32%	£274.29
2016	364,089	20.60	3.33	£87,140.72	2456.70	£84,684.02	-£232,213.46	5	-18%	£384.04
2017	364,089	20.81	3.36	£88,012.13	2554.97	£85,457.16	-£146,756.30	6	-9%	£494.49
2018	364,089	21.02	3.40	£88,892.25	2657.17	£86,235.08	-£60,521.22	7	-3%	£605.62
2019	364,089	21.23	3.43	£89,781.17	2763.46	£87,017.72	£26,496.50	8	1%	£717.43
2020	364,089	21.44	3.47	£90,678.99	2874.00	£87,804.99	£114,301.49	9	4%	£829.90
2021	364,089	21.65	3.50	£91,585.78	2988.95	£88,596.82	£202,898.31	10	7%	£943.02
2022	364,089	21.87	3.53	£92,501.63	3108.51	£89,393.12	£292,291.43	11	8%	£1,056.77
2022	364,089	22.09	3.57	£93,426.65	3232.85	£90,193.80	£382,485.22	12	10%	£1,171.15
2022	364,089	22.31	3.61	£94,360.92	3362.17	£90,998.75	£473,483.97	13	11%	£1,286.15
2022	364,089	22.53	3.64	£95,304.52	3496.65	£91,807.87	£565,291.84	14	11%	£1,401.74
2022	364,089	22.76	3.68	£96,257.57	3636.52	£92,621.05	£657,912.89	15	12%	£1,517.91
2022	364,089	22.99	3.72	£97,220.15	3781.98	£93,438.16	£751,351.06	16	13%	£1,634.64
2022	364,089	23.22	3.75	£98,192.35	3933.26	£94,259.09	£845,610.14	17	13%	£1,751.91
2022	364,089	23.45	3.79	£99,174.27	4090.59	£95,083.68	£940,693.82	18	13%	£1,869.71
2022	364,089	23.68	3.83	£100,166.01	4254.21	£95,911.80	£1,036,605.62	19	14%	£1,988.01
2022	364,089	23.92	3.87	£101,167.67	4424.38	£96,743.29	£1,133,348.91	20	14%	£2,106.80

Table 20: Financial Analysis for Scenario 2 with a 200mm pipe, turbine efficiency reduced by 10%

Scenario 2, 200mm pipe										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	615,530	19.80	3.20	£141,571.99	2100.00	-£508,528.01	-£508,528.01	1	-	-
2013	615,530	20.00	3.23	£142,987.71	2184.00	£140,803.71	-£367,724.30	2	-	£9,474.04
2014	615,530	20.20	3.26	£144,417.59	2271.36	£142,146.23	-£225,578.08	3	-32%	£9,665.82
2015	615,530	20.40	3.30	£145,861.76	2362.21	£143,499.55	-£82,078.53	4	-8%	£9,859.16
2016	615,530	20.60	3.33	£147,320.38	2456.70	£144,863.68	£62,785.14	5	5%	£10,054.03
2017	615,530	20.81	3.36	£148,793.58	2554.97	£146,238.61	£209,023.76	6	13%	£10,250.45
2018	615,530	21.02	3.40	£150,281.52	2657.17	£147,624.35	£356,648.10	7	18%	£10,448.41
2019	615,530	21.23	3.43	£151,784.33	2763.46	£149,020.88	£505,668.98	8	21%	£10,647.92
2020	615,530	21.44	3.47	£153,302.18	2874.00	£150,428.18	£656,097.16	9	23%	£10,848.96
2021	615,530	21.65	3.50	£154,835.20	2988.95	£151,846.24	£807,943.41	10	24%	£11,051.54
2022	615,530	21.87	3.53	£156,383.55	3108.51	£153,275.04	£961,218.45	11	25%	£11,255.65
2022	615,530	22.09	3.57	£157,947.39	3232.85	£154,714.53	£1,115,932.98	12	26%	£11,461.30
2022	615,530	22.31	3.61	£159,526.86	3362.17	£156,164.69	£1,272,097.67	13	27%	£11,668.46
2022	615,530	22.53	3.64	£161,122.13	3496.65	£157,625.47	£1,429,723.14	14	27%	£11,877.15
2022	615,530	22.76	3.68	£162,733.35	3636.52	£159,096.83	£1,588,819.97	15	28%	£12,087.34
2022	615,530	22.99	3.72	£164,360.68	3781.98	£160,578.70	£1,749,398.68	16	28%	£12,299.04
2022	615,530	23.22	3.75	£166,004.29	3933.26	£162,071.03	£1,911,469.71	17	28%	£12,512.22
2022	615,530	23.45	3.79	£167,664.33	4090.59	£163,573.74	£2,075,043.45	18	28%	£12,726.90
2022	615,530	23.68	3.83	£169,340.98	4254.21	£165,086.76	£2,240,130.21	19	28%	£12,943.04
2022	615,530	23.92	3.87	£171,034.39	4424.38	£166,610.00	£2,406,740.21	20	28%	£13,160.65

Table 21: Financial Analysis for Scenario 2 with a 250mm pipe, turbine efficiency reduced by 10%

Scenario 2, 250mm										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	642,513	19.80	3.20	£147,778.05	2100.00	-£502,321.95	-£502,321.95	1	-	-
2013	642,513	20.00	3.23	£149,255.83	2184.00	£147,071.83	-£355,250.12	2	-	£10,369.48
2014	642,513	20.20	3.26	£150,748.39	2271.36	£148,477.03	-£206,773.09	3	-29%	£10,570.22
2015	642,513	20.40	3.30	£152,255.87	2362.21	£149,893.66	-£56,879.43	4	-6%	£10,772.60
2016	642,513	20.60	3.33	£153,778.43	2456.70	£151,321.73	£94,442.30	5	7%	£10,976.61
2017	642,513	20.81	3.36	£155,316.22	2554.97	£152,761.24	£247,203.54	6	15%	£11,182.26
2018	642,513	21.02	3.40	£156,869.38	2657.17	£154,212.21	£401,415.75	7	20%	£11,389.54
2019	642,513	21.23	3.43	£158,438.07	2763.46	£155,674.62	£557,090.36	8	23%	£11,598.45
2020	642,513	21.44	3.47	£160,022.45	2874.00	£157,148.46	£714,238.82	9	25%	£11,809.00
2021	642,513	21.65	3.50	£161,622.68	2988.95	£158,633.72	£872,872.54	10	26%	£12,021.18
2022	642,513	21.87	3.53	£163,238.90	3108.51	£160,130.39	£1,033,002.94	11	27%	£12,234.99
2022	642,513	22.09	3.57	£164,871.29	3232.85	£161,638.44	£1,194,641.37	12	28%	£12,450.43
2022	642,513	22.31	3.61	£166,520.01	3362.17	£163,157.84	£1,357,799.21	13	29%	£12,667.48
2022	642,513	22.53	3.64	£168,185.21	3496.65	£164,688.55	£1,522,487.76	14	29%	£12,886.16
2022	642,513	22.76	3.68	£169,867.06	3636.52	£166,230.54	£1,688,718.30	15	29%	£13,106.44
2022	642,513	22.99	3.72	£171,565.73	3781.98	£167,783.75	£1,856,502.05	16	30%	£13,328.33
2022	642,513	23.22	3.75	£173,281.39	3933.26	£169,348.13	£2,025,850.17	17	30%	£13,551.81
2022	642,513	23.45	3.79	£175,014.20	4090.59	£170,923.61	£2,196,773.78	18	30%	£13,776.88
2022	642,513	23.68	3.83	£176,764.34	4254.21	£172,510.13	£2,369,283.91	19	30%	£14,003.52
2022	642,513	23.92	3.87	£178,531.99	4424.38	£174,107.60	£2,543,391.51	20	30%	£14,231.74

Table 22: Financial Analysis for Scenario 2 with a 300mm pipe, turbine efficiency reduced by 10%

Scenario 2, 300mm pipe extension										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	663,979	19.80	3.20	£152,715.07	2100.00	-£497,384.93	-£497,384.93	1	-	-
2013	663,979	20.00	3.23	£154,242.22	2184.00	£152,058.22	-£345,326.72	2	-	£11,081.82
2014	663,979	20.20	3.26	£155,784.64	2271.36	£153,513.28	-£191,813.44	3	-27%	£11,289.69
2015	663,979	20.40	3.30	£157,342.49	2362.21	£154,980.27	-£36,833.17	4	-4%	£11,499.26
2016	663,979	20.60	3.33	£158,915.91	2456.70	£156,459.21	£119,626.04	5	9%	£11,710.54
2017	663,979	20.81	3.36	£160,505.07	2554.97	£157,950.10	£277,576.14	6	17%	£11,923.52
2018	663,979	21.02	3.40	£162,110.12	2657.17	£159,452.95	£437,029.09	7	21%	£12,138.21
2019	663,979	21.23	3.43	£163,731.22	2763.46	£160,967.76	£597,996.85	8	24%	£12,354.62
2020	663,979	21.44	3.47	£165,368.53	2874.00	£162,494.54	£760,491.39	9	26%	£12,572.73
2021	663,979	21.65	3.50	£167,022.22	2988.95	£164,033.26	£924,524.65	10	28%	£12,792.54
2022	663,979	21.87	3.53	£168,692.44	3108.51	£165,583.93	£1,090,108.58	11	29%	£13,014.07
2022	663,979	22.09	3.57	£170,379.37	3232.85	£167,146.51	£1,257,255.09	12	30%	£13,237.29
2022	663,979	22.31	3.61	£172,083.16	3362.17	£168,720.99	£1,425,976.09	13	30%	£13,462.22
2022	663,979	22.53	3.64	£173,803.99	3496.65	£170,307.34	£1,596,283.42	14	30%	£13,688.84
2022	663,979	22.76	3.68	£175,542.03	3636.52	£171,905.51	£1,768,188.93	15	31%	£13,917.15
2022	663,979	22.99	3.72	£177,297.45	3781.98	£173,515.47	£1,941,704.40	16	31%	£14,147.14
2022	663,979	23.22	3.75	£179,070.43	3933.26	£175,137.16	£2,116,841.57	17	31%	£14,378.82
2022	663,979	23.45	3.79	£180,861.13	4090.59	£176,770.54	£2,293,612.10	18	31%	£14,612.15
2022	663,979	23.68	3.83	£182,669.74	4254.21	£178,415.53	£2,472,027.63	19	31%	£14,847.15
2022	663,979	23.92	3.87	£184,496.44	4424.38	£180,072.05	£2,652,099.69	20	31%	£15,083.80

Table 23: Financial Analysis for Scenario 1, turbine efficiency increased by 10%

Scenario 1										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**£**	**%**	**%**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	297,891	19.80	3.20	£68,514.97	2100.00	-£581,585.03	-£581,585.03	1	-	-
2013	297,891	20.00	3.23	£69,200.12	2184.00	£67,016.12	-£514,568.91	2	-	-£2,139.94
2014	297,891	20.20	3.26	£69,892.12	2271.36	£67,620.76	-£446,948.14	3	-	-£2,053.56
2015	297,891	20.40	3.30	£70,591.04	2362.21	£68,228.83	-£378,719.31	4	-	-£1,966.70
2016	297,891	20.60	3.33	£71,296.95	2456.70	£68,840.25	-£309,879.06	5	-25%	-£1,879.35
2017	297,891	20.81	3.36	£72,009.92	2554.97	£69,454.95	-£240,424.11	6	-15%	-£1,791.54
2018	297,891	21.02	3.40	£72,730.02	2657.17	£70,072.85	-£170,351.25	7	-9%	-£1,703.27
2019	297,891	21.23	3.43	£73,457.32	2763.46	£70,693.87	-£99,657.39	8	-4%	-£1,614.55
2020	297,891	21.44	3.47	£74,191.90	2874.00	£71,317.90	-£28,339.49	9	-1%	-£1,525.40
2021	297,891	21.65	3.50	£74,933.82	2988.95	£71,944.86	£43,605.38	10	1%	-£1,435.84
2022	297,891	21.87	3.53	£75,683.15	3108.51	£72,574.64	£116,180.02	11	3%	-£1,345.87
2022	297,891	22.09	3.57	£76,439.99	3232.85	£73,207.13	£189,387.15	12	5%	-£1,255.51
2022	297,891	22.31	3.61	£77,204.39	3362.17	£73,842.22	£263,229.37	13	6%	-£1,164.79
2022	297,891	22.53	3.64	£77,976.43	3496.65	£74,479.78	£337,709.14	14	7%	-£1,073.71
2022	297,891	22.76	3.68	£78,756.19	3636.52	£75,119.67	£412,828.82	15	8%	-£982.29
2022	297,891	22.99	3.72	£79,543.76	3781.98	£75,761.77	£488,590.59	16	9%	-£890.56
2022	297,891	23.22	3.75	£80,339.19	3933.26	£76,405.93	£564,996.52	17	9%	-£798.54
2022	297,891	23.45	3.79	£81,142.59	4090.59	£77,051.99	£642,048.52	18	10%	-£706.25
2022	297,891	23.68	3.83	£81,954.01	4254.21	£77,699.80	£719,748.31	19	10%	-£613.70
2022	297,891	23.92	3.87	£82,773.55	4424.38	£78,349.17	£798,097.48	20	10%	-£520.94

Table 24: Financial Analysis for Scenario 2 with a 200mm pipe, turbine efficiency increased by 10%

Scenario 2, 200mm pipe										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	503,616	19.80	3.20	£115,831.63	2100.00	-£534,268.37	-£534,268.37	1	-	-
2013	503,616	20.00	3.23	£116,989.94	2184.00	£114,805.94	-£419,462.43	2	-	£5,760.07
2014	503,616	20.20	3.26	£118,159.84	2271.36	£115,888.48	-£303,573.95	3	-41%	£5,914.72
2015	503,616	20.40	3.30	£119,341.44	2362.21	£116,979.23	-£186,594.72	4	-19%	£6,070.54
2016	503,616	20.60	3.33	£120,534.86	2456.70	£118,078.15	-£68,516.57	5	-5%	£6,227.53
2017	503,616	20.81	3.36	£121,740.20	2554.97	£119,185.23	£50,668.66	6	3%	£6,385.68
2018	503,616	21.02	3.40	£122,957.61	2657.17	£120,300.44	£170,969.10	7	8%	£6,545.00
2019	503,616	21.23	3.43	£124,187.18	2763.46	£121,423.73	£292,392.83	8	12%	£6,705.47
2020	503,616	21.44	3.47	£125,429.05	2874.00	£122,555.06	£414,947.88	9	15%	£6,867.09
2021	503,616	21.65	3.50	£126,683.34	2988.95	£123,694.39	£538,642.27	10	17%	£7,029.85
2022	503,616	21.87	3.53	£127,950.18	3108.51	£124,841.66	£663,483.94	11	18%	£7,193.74
2022	503,616	22.09	3.57	£129,229.68	3232.85	£125,996.83	£789,480.77	12	19%	£7,358.77
2022	503,616	22.31	3.61	£130,521.98	3362.17	£127,159.81	£916,640.57	13	20%	£7,524.91
2022	503,616	22.53	3.64	£131,827.20	3496.65	£128,330.54	£1,044,971.12	14	20%	£7,692.16
2022	503,616	22.76	3.68	£133,145.47	3636.52	£129,508.95	£1,174,480.06	15	21%	£7,860.50
2022	503,616	22.99	3.72	£134,476.92	3781.98	£130,694.94	£1,305,175.01	16	21%	£8,029.93
2022	503,616	23.22	3.75	£135,821.69	3933.26	£131,888.43	£1,437,063.44	17	21%	£8,200.43
2022	503,616	23.45	3.79	£137,179.91	4090.59	£133,089.32	£1,570,152.75	18	22%	£8,371.98
2022	503,616	23.68	3.83	£138,551.71	4254.21	£134,297.49	£1,704,450.25	19	22%	£8,544.58
2022	503,616	23.92	3.87	£139,937.23	4424.38	£135,512.84	£1,839,963.09	20	22%	£8,718.20

Table 25: Financial Analysis for Scenario 2 with a 250mm pipe, turbine efficiency increased by 10%

Scenario 2, 250mm										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	525,693	19.80	3.20	£120,909.31	2100.00	-£529,190.69	-£529,190.69	1	-	-
2013	525,693	20.00	3.23	£122,118.41	2184.00	£119,934.41	-£409,256.28	2	-	£6,492.71
2014	525,693	20.20	3.26	£123,339.59	2271.36	£121,068.23	-£288,188.05	3	-	£6,654.68
2015	525,693	20.40	3.30	£124,572.99	2362.21	£122,210.77	-£165,977.28	4	-17%	£6,817.90
2016	525,693	20.60	3.33	£125,818.72	2456.70	£123,362.01	-£42,615.26	5	-3%	£6,982.37
2017	525,693	20.81	3.36	£127,076.90	2554.97	£124,521.93	£81,906.67	6	5%	£7,148.07
2018	525,693	21.02	3.40	£128,347.67	2657.17	£125,690.50	£207,597.17	7	10%	£7,315.01
2019	525,693	21.23	3.43	£129,631.15	2763.46	£126,867.69	£334,464.87	8	14%	£7,483.18
2020	525,693	21.44	3.47	£130,927.46	2874.00	£128,053.47	£462,518.33	9	16%	£7,652.57
2021	525,693	21.65	3.50	£132,236.74	2988.95	£129,247.78	£591,766.11	10	18%	£7,823.19
2022	525,693	21.87	3.53	£133,559.10	3108.51	£130,450.59	£722,216.70	11	19%	£7,995.02
2022	525,693	22.09	3.57	£134,894.69	3232.85	£131,661.84	£853,878.54	12	20%	£8,168.05
2022	525,693	22.31	3.61	£136,243.64	3362.17	£132,881.47	£986,760.02	13	21%	£8,342.29
2022	525,693	22.53	3.64	£137,606.08	3496.65	£134,109.42	£1,120,869.44	14	22%	£8,517.71
2022	525,693	22.76	3.68	£138,982.14	3636.52	£135,345.62	£1,256,215.06	15	22%	£8,694.31
2022	525,693	22.99	3.72	£140,371.96	3781.98	£136,589.98	£1,392,805.04	16	22%	£8,872.07
2022	525,693	23.22	3.75	£141,775.68	3933.26	£137,842.42	£1,530,647.46	17	23%	£9,050.99
2022	525,693	23.45	3.79	£143,193.44	4090.59	£139,102.85	£1,669,750.30	18	23%	£9,231.06
2022	525,693	23.68	3.83	£144,625.37	4254.21	£140,371.16	£1,810,121.46	19	23%	£9,412.24
2022	525,693	23.92	3.87	£146,071.62	4424.38	£141,647.24	£1,951,768.70	20	23%	£9,594.54

Table 26: Financial Analysis for Scenario 2 with a 300mm pipe, turbine efficiency increased by 10%

Scenario 2, 300mm pipe extension										
Units	**kWh**	**p/kWh**	**p/kWh**	**£**	**£**	**£**	**£**	**#**	**%**	**£**
Year	**Generation**	**Generation Tariff**	**Fixed Export**	**Total Revenue**	**Maintenance**	**Cash Flow**	**Cumulative Cash Flows**	**Year No.**	**IRR (Internal discount rate)**	**NPV**
2012	543,255	19.80	3.20	£124,948.69	2100.00	-£525,151.31	-£525,151.31	1	-	-
2013	543,255	20.00	3.23	£126,198.18	2184.00	£124,014.18	-£401,137.13	2	-	£7,075.53
2014	543,255	20.20	3.26	£127,460.16	2271.36	£125,188.80	-£275,948.33	3	-38%	£7,243.33
2015	543,255	20.40	3.30	£128,734.76	2362.21	£126,372.55	-£149,575.79	4	-15%	£7,412.44
2016	543,255	20.60	3.33	£130,022.11	2456.70	£127,565.41	-£22,010.38	5	-2%	£7,582.85
2017	543,255	20.81	3.36	£131,322.33	2554.97	£128,767.36	£106,756.98	6	6%	£7,754.56
2018	543,255	21.02	3.40	£132,635.55	2657.17	£129,978.38	£236,735.36	7	12%	£7,927.56
2019	543,255	21.23	3.43	£133,961.91	2763.46	£131,198.45	£367,933.81	8	15%	£8,101.86
2020	543,255	21.44	3.47	£135,301.53	2874.00	£132,427.53	£500,361.34	9	18%	£8,277.44
2021	543,255	21.65	3.50	£136,654.54	2988.95	£133,665.59	£634,026.93	10	19%	£8,454.30
2022	543,255	21.87	3.53	£138,021.09	3108.51	£134,912.58	£768,939.51	11	21%	£8,632.45
2022	543,255	22.09	3.57	£139,401.30	3232.85	£136,168.45	£905,107.95	12	21%	£8,811.86
2022	543,255	22.31	3.61	£140,795.31	3362.17	£137,433.14	£1,042,541.10	13	22%	£8,992.53
2022	543,255	22.53	3.64	£142,203.26	3496.65	£138,706.61	£1,181,247.71	14	23%	£9,174.45
2022	543,255	22.76	3.68	£143,625.30	3636.52	£139,988.78	£1,321,236.48	15	23%	£9,357.62
2022	543,255	22.99	3.72	£145,061.55	3781.98	£141,279.57	£1,462,516.05	16	23%	£9,542.02
2022	543,255	23.22	3.75	£146,512.17	3933.26	£142,578.91	£1,605,094.96	17	24%	£9,727.64
2022	543,255	23.45	3.79	£147,977.29	4090.59	£143,886.70	£1,748,981.66	18	24%	£9,914.46
2022	543,255	23.68	3.83	£149,457.06	4254.21	£145,202.85	£1,894,184.50	19	24%	£10,102.48
2022	543,255	23.92	3.87	£150,951.63	4424.38	£146,527.25	£2,040,711.75	20	24%	£10,291.68

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