SKELLIG MICHAEL LOWER LIGHTHOUSE

Fabric Retrofit Strategy for Improved Energy Efficiency

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1 Introduction

This report has been prepared in response to instruction by Mr Fergus Mc Cormick, Senior Architect of the Mallow & Killarney National Monuments Districts for the Office of Public Works (OPW) and sets forth a high-level fabric retrofit strategy for the Lower Lighthouse on Great Skellig Island, County Kerry. As historic building consultants, Carrig Conservation International Ltd have been procured to provide a retrofit strategy for the building fabric that respects both the heritage value and physical properties of the building. In line with the project brief, recommendations have been provided to improve the thermal efficiency of the building as far as is reasonably practicable without jeopardising the material stability or historic character of the building. The renewable and energy system strategy provided by ARUP has been reviewed and further comments have been provided with reference to conservation considerations and the proposed fabric retrofit strategy.

When altering an historic building to improve its thermal efficiency, it is of utmost importance that the specified material and system upgrades are based on best practice guidance and research, and where possible, measured data. A holistic retrofit approach must also balance concerns relating to the heritage conservation, fabric preservation, energy performance, embodied and operational carbon emissions and occupant wellbeing. The procedure recommended by I.S. EN 16883:2017 *Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings* has been used to identify the most suitable upgrade options. The goal of this strategy is to improve the thermal efficiency and reduce carbon emissions as much as possible while minimising the likelihood that any unintended consequences will result from the proposed works. The methodology that follows details the steps and requirements of this holistic retrofit approach.

This Retrofit Strategy may be used by the project coordinators to tender for a design team for the next stage of works, who when appointed, will deliver this strategy and develop detailed specifications. It will be of utmost importance that the design team and contractors have experience working with traditional and protected structures. This requirement should form part of any tendering evaluation process and experience should be suitably weighted.

2 Building Details

Building name: Skellig Michael Lower Lighthouse

Location: Great Skellig Island, County Kerry

Construction dates: 1821-1826

Designer: Inspector George Halpin, Commissioners of Irish Lights

Orientation: Front elevation of the lighthouse faces northwest

Original construction: Locally quarried rubble masonry with slate cladding on outside walls; pitched roof with attic space; imported granite for lantern blocking, tower, floors, stairs, windowsills and certain wall copings; tower and dwelling were painted white

Material changes: Pitched roof flattened in 1910; slate cladding removed and masonry walls rendered with lime; 1962 refurbishment of interior and demolition and reconstruction of the tower and engine room designed by Engineer-in-Chief Mr A.D.H. Martin

Floor area: 230 m^2 (as existing)

Number of storeys: 2

Thermal improvements to date:

Walls: none

Roof: none

Windows: none

Floors: none

Heating & hot water fuel: diesel generator

Lighting: electric powered by the diesel generator

Previous function: Lighthouse and accommodation for the lighthouse keeper and family

Proposed function: Accommodation for OPW staff, workers and consultants

Expected hours of use: Full-time April - October

Number of building users: 14

Heritage Designation: The lighthouse sits within the Skellig Michael World Heritage Site boundaries (inscribed 1993) (*Skellig Michael World Heritage Site Management Plan 2008-2018*, 2008)

Planning Authority: Kerry County Council

3 Site History

The Lower Lighthouse is located on the western edge of the southern tip of Great Skellig Island overlooking Seal Cove. Great Skellig Island is located 8 miles (12.8 km) from the nearest mainland point. The building is accessed from the approach road from the East Landing at Blind Man's Cove.

Construction began on the lighthouse in August 1821 and was completed in 1826. Inspector of Works and Inspector of Lighthouses George Halpin designed the buildings, rock cuttings and roadways. The lighthouse dwellings and tower were constructed of local rubble masonry with slate tile cladding on the exterior walls. Granite was imported from the mainland for the lantern block, tower, floors, stairs, window sills and certain wall copings. The building was divided into two dwellings – one for the Principle Keeper and one for the Keeper's Assistant. The pitched roof seen in the photo below was flattened in 1910.

A photo album from the Commissioners of Irish Lights contains historic photos of the Lower Lighthouse in 1903, showing the pitched roof and two cast iron porticos (Figure 1 and Figure 2) (*Commissioners of Irish Lights - Album 3*, 1903).

Figure 1. Lower Lighthouse on Great Skellig Island, 1903. (Commissioners of Irish Lights – Album 3, 1903).

Figure 2. 1903 photo of the Lower Lighthouse showing a pitched roof with a central chimney and two cast iron porticos. (Commissioners of Irish Lights – Album 3, 1903).

Significant refurbishment works were undertaken in 1962, which included the demolition and reconstruction of the 1826 tower and the 1924 connecting corridor. The corridor was replaced with an engine room. Electric lighting, central heating, indoor toilets and an office for the Principal Keeper were also added at this time.

In 1987, the Lower Lighthouse was converted to an unmanned electric station. Aside from the interests of the Commissioners of Irish Lights, Great Skellig Island was sold to the Board of Works. In 2001, the light was converted to solar power with two diesel generators as back-up, which also provide heating and power for the dwelling.

4 Local Environmental Conditions

The nearest weather station to Great Skellig Island is the Valentia Observatory. The mean annual rainfall for Valentia Island from 2017 through 2019 was 1689.4mm, which is 937mm more on average than what fell on Dublin over the same period (Table 1) (Met Éireann, 2020).

Table 1. Annual rainfall for Valentia Observatory versus Dublin Airport (Met Éireann, 2020).

Total rainfall in millimetres for VALENTIA OBSERVATORY

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2020	146.3	237.6	115.8	60.1	52.6	127.4	214.0	219.7	94.5	200.9			1468.9
2019	134.3	149.8	175.3	96.8	49.0	58.0	83.7	203.9	176.9	202.4	171.7	199.8	1701.6
2018	238.2	119.1	130.6	204.5	114.3	39.2	50.1	109.4	118.8	114.7	253.4	278.6	1770.9
2017	167.2	138.7	135.1	51.4	77.8	141.5	108.4	102.8	204.4	162.2	107.4	198.8	1595.7
mean	173.8	123.7	123.8	96.7	93.5	95.3	99.0	114.9	125.4	177.1	169.3	164.9	1557.4

Total rainfall in millimetres for DUBLIN AIRPORT

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2020	36.0	130.4	31.8	12.8	9.3	69.6	98.9	87.3	60.9	77.4			614.4
2019	26.8	30.5	92.5	74.6	33.4	82.9	41.0	91.9	104.6	77.2	173.0	57.7	886.1
2018	93.1	36.9	100.0	68.9	19.1	4.8	40.0	48.0	43.8	42.6	131.2	81.0	709.4
2017	21.9	41.6	67.2	10.0	43.5	86.4	42.2	73.2	82.3	47.8	81.5	63.1	660.7
mean	62.6	48.8	52.6	54.1	59.5	66.7	56.2	73.3	59.5	79.0	72.9	72.7	757.9

Inversely, Valentia Island receives approximately the same amount or slightly more solar radiation than Dublin Airport annually (Table 2), which may mean that despite the extra rainfall solar renewables could still be cost effective in this area of the country.

Table 2. Annual solar radiation levels for Valentia Island versus Dublin Airport(Met Éireann, 2020).

Global Solar Radiation in Joules/cm^2 for VALENTIA OBSERVATORY

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2020	8044	12272	27793	46503	61004	43997	47562	42877	30006	18363			338421
2019	7372	12737	25975	38951	55040	57600	53528	38142	31335	20199	9325	6024	356228
2018	7734	15561	28509	37936	54430	63534	59870	37021	30163	20475	10113	4836	370182
2017	7687	12801	25889	43882	53681	47828	45494	40505	29306	14329	8937	5188	335527
mean	7381	13059	25500	41291	53914	53694	50133	43319	30729	17942	8986	5843	351794

Global Solar Radiation in Joules/cm^2 for DUBLIN AIRPORT

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2020	7855	14719	28920	45326	68134	45786	45459	36785	31561	18361			342906
2019	6794	15172	28541	35758	48344	51880	53387	45175	32004	18607	7018	5534	348214
2018	7475	14655	21659	36294	56900	64896	52340	39995	32175	19493	6936	4254	357072
2017	6701	10573	26799	33437	57196	51592	52843	39665	29850	15686	9640	5499	339481
mean	7228	12761	25705	39407	52530	52648	50860	42506	30043	18168	8935	5550	346340

The following diagram from the Department of Culture, Heritage and the Gaeltacht's *Climate Change Sectoral Adaptation Plan for Built and Archaeological Heritage* outlines the observed and projected climate-related impacts identified for Ireland (Figure 3) (Daly *et al.*, 2019).

As climate change is projected to cause wetter winters with more severe storms and heavier rainfall, special attention will need to be given to the rainwater goods and drainage systems at the Lower Lighthouse to ensure the building fabric is able to dry out as soon as possible, especially given that the building will not be in use during the winter months.

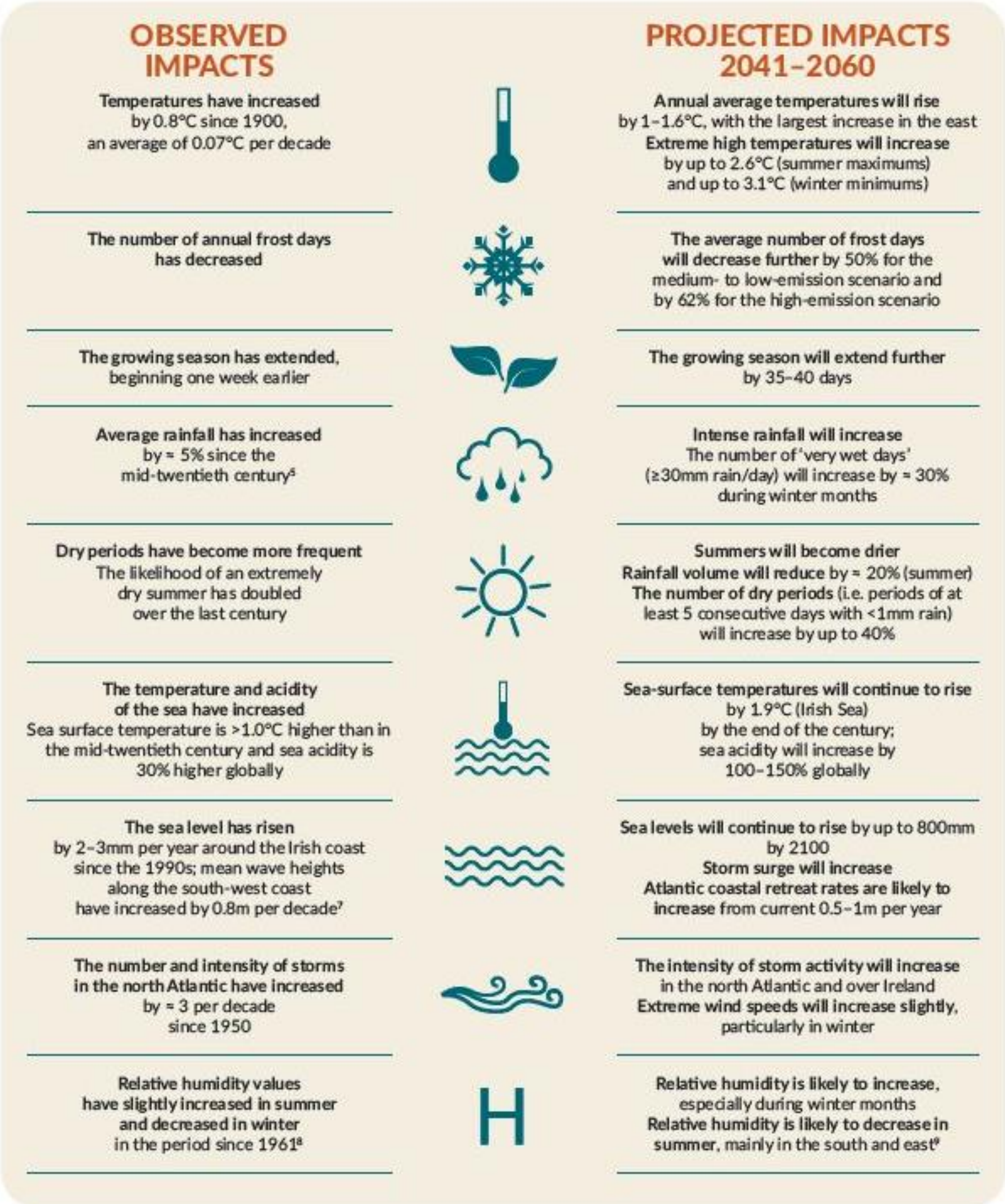


Figure 3. Summary of observed and projected climate change impacts in Ireland (Daly et al., 2019).

5 Methodology

In order to develop a customised Fabric Retrofit Strategy in response to the conditions found at the Skellig Michael Lower Lighthouse, the following steps were undertaken:

- Meeting with the OPW project teams to review the project objectives;
- On-site assessment of the building's current condition;
- Assessment of the adaptive capacity of the building towards optimum thermal efficiency;
- Development of a low carbon Fabric Retrofit Strategy for the building;
- Final technical discussion with the OPW project team to review the draft Retrofit Strategy.

5.1 Review of the Project Objectives

Carrig met with the OPW project team on the 9th of July 2019 at the OPW offices on St Stephen's Green to discuss the project scope and objectives. The parameters of Carrig's fabric retrofit strategy were discussed and agreed at this meeting.

5.2 Condition Assessment

Carrig visited the Lower Lighthouse on 12 August 2020 to undertake a selective condition assessment. This site visit was undertaken to understand the building's construction, present condition and to inspect relevant areas that may present hygrothermal challenges.

CAD drawings were supplied to Carrig by the OPW, on which Carrig has marked up existing conditions to highlight areas of concern that may present difficulties or restrictions in relation to thermal upgrade options (see Section 6.5). Information gathered from the condition assessment has also been used to eliminate, where possible, any adverse effects to performance and/or historic fabric.

5.3 Assessment of Adaptive Capacity

Prior to developing the fabric retrofit strategy for the building, Carrig assessed the adaptive capacity of the building. All measures to improve the thermal efficiency and to reduce carbon emissions have been evaluated against their potential to compromise the historic or aesthetic significance of the building.

Using the findings from the condition assessment, the representative u-value calculation for the walls and a review of best practice guidance, a short list of proposed retrofit measures was created. These measures were then assessed according to the thermal benefits, potential risks and level of impact they pose (see Section 7.3). This assessment is based on the methodology proposed by I.S. EN 16883:2017 *Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings*.

5.4 Development of the Fabric Retrofit Strategy

The Fabric Retrofit Strategy for the Lower Lighthouse has been developed in line with the latest research and best practice guidance. The strategy has given preference to low-risk, high-impact measures that are suitable for traditional and historic buildings and that have a low or neutral environmental impact.

Prior to the development of detailed specifications, clear objectives and targets must be agreed with the design team and building owners. The objectives and targets for energy use should be developed in collaboration with an engineering team experienced with low carbon energy systems and their application within historic buildings.

All building works will lead to a spike in embodied carbon emissions due to the removal of old materials and systems and the installation of new materials and systems. It is therefore important that materials with low embodied emissions are given preference and that the upgrade works and new energy systems will lead to lower operational emissions after the retrofit is complete.

To fully understand the environmental impact of the refurbishment works, a full life cycle assessment should be completed during the concept design phase of the project. This will require detailed drawings, specifications and a full bill of quantities.

Only those measures that comply with the physical and heritage requirements of the building have been included in the Fabric Retrofit Strategy (see Section 7.5). In line with conservation convention, any intervention must be as reversible as possible and a cautious approach of doing 'as much as necessary and as little as possible' has been followed. Low carbon materials and works have been prioritised wherever possible.

5.5 Technical Discussion

Following the on-site condition assessment and submission of the final Fabric Retrofit Strategy, Carrig would like to meet with the OPW project team to discuss our recommendations, any particular concerns and what we hope can be achieved within the building and budgetary constraints.

6 Condition Assessment

A Condition Assessment of the Lower Lighthouse was conducted on 12 August 2020. The key findings are outlined below and areas of concern have been marked out on the plans of the building (see Section 6.5). The limitations these findings present have been accounted for as part of the *Retrofit Impact Assessment* under Section 7.3.

6.1 Floors

The ground floor is poured concrete (250mm thick) with asbestos tiles in some rooms and the first floor has suspended timber floors throughout. The condition of the concrete floor ranges from acceptable to bad, with about 35% in bad condition. All timber floors were deemed to be in acceptable condition.

Figure 4. Poured concrete floor at ground floor level with a portion of tiles remaining in place (Carrig, 2020).

6.2 Walls

Five wall build-ups were found throughout the property:

- Rubble masonry with lime render
- Exposed rubble masonry/brick
- Concrete block with internal plasterboard
- Concrete block with cement render
- Exposed concrete block

The majority of the walls in the original 1826 building are solid masonry with brick or concrete block infill while the 1962 corridor and lighthouse tower are constructed of concrete block. Samples of external render were taken from two locations on the front façade facing Seal Cove (see Figure 11 in Section 6.5). The samples differ in the type of aggregate used and the proportion of aggregate to binder. Both were applied to a semi-smooth finish.

Further details of the material properties of these renders and other samples taken from the Lower Lighthouse can be found in the *Lab Report on Geological Analysis of 5 Rock, Mortar and Render Samples*, which should be read in tandem with this strategy.

Figure 5. Random rubble external walls with brick window surrounds on the first floor (Carrig, 2020).

The internal spaces have been largely stripped by the OPW in preparation of upgrade works, however some internal lath and plaster and plasterboard remains in place. Samples of the plaster should be taken to determine whether concrete is present in the mix. If so, it may be a later installation on earlier lath.

Figure 6. Lath and lime plaster in-situ on an internal wall on the first floor (Carrig, 2020).

Two notable areas of damp were found in the ground floor walls as marked with yellow boxes on the ground floor plan of the condition assessment (see Section 6.5). The collection and dispersal of rainwater around these points will likely need to be improved.

6.3 Windows & Doors

The windows in the older building are timber framed and single glazed and are in acceptable condition. Some internal timber doors are still in place, but most internal timber joinery has been stripped out. Existing windows will benefit from repairs and draughtproofing to improve the fit and seal around the frames.

Figure 7. Typical historic timber framed singled glazed window (Carrig, 2020).
Figure 8. Timber door and transom window on the ground floor (Carrig, 2020).

6.4 Roof

The original pitched roof as shown in Figure 1 and Figure 2 was replaced with a flat reinforced concrete roof in 1910. The concrete has spalled where the steel mesh has corroded and the steel I-beam supports are showing signs of corrosion where they meet the walls.

Figure 9. Underside of the reinforced concrete roof. Both the reinforcing mesh and steel I-beam supports are showing signs of corrosion (Carrig, 2020).

6.5 Condition Assessment Drawings

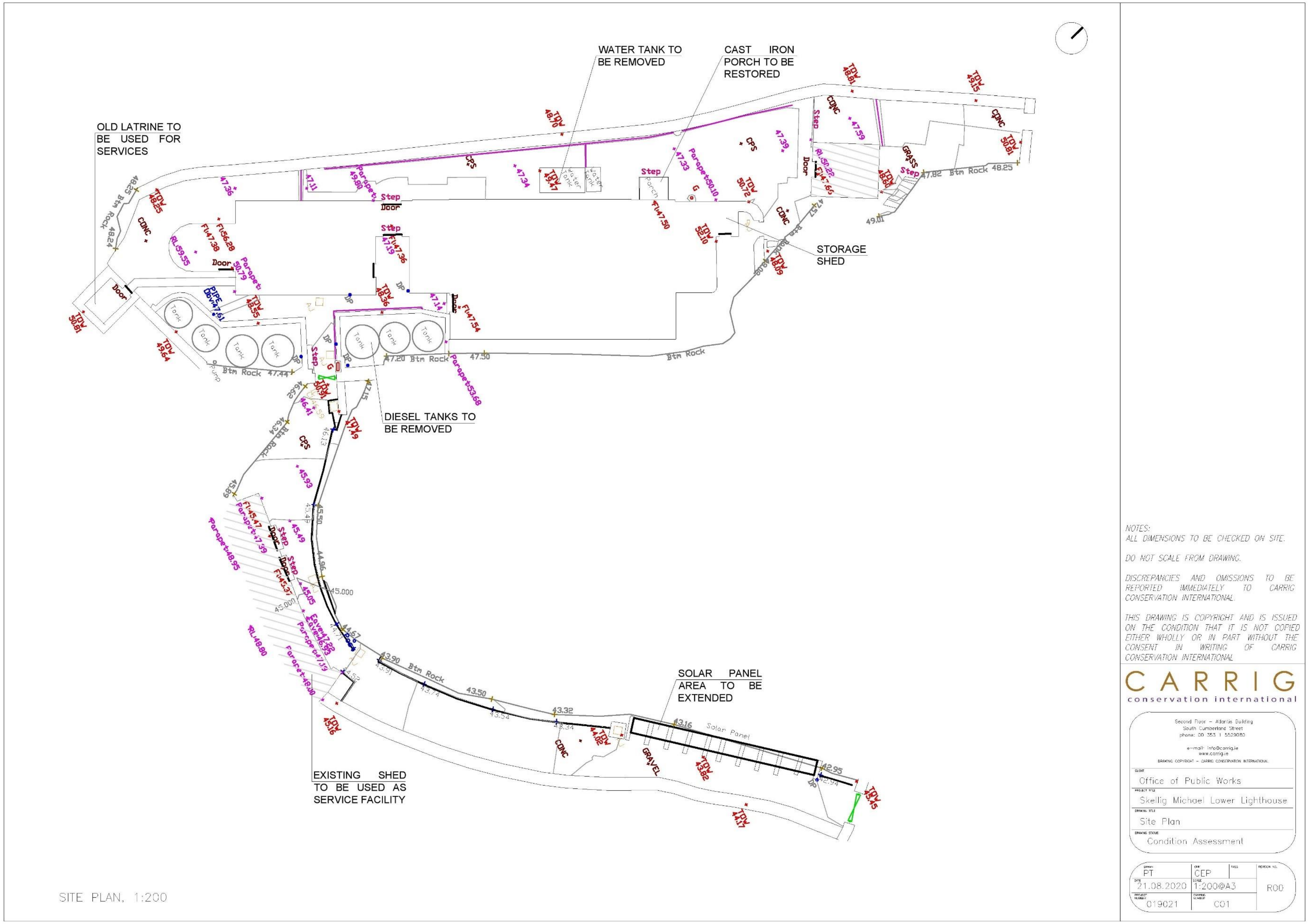


Figure 10. Condition Assessment – Site Plan (Carrig, 2020).

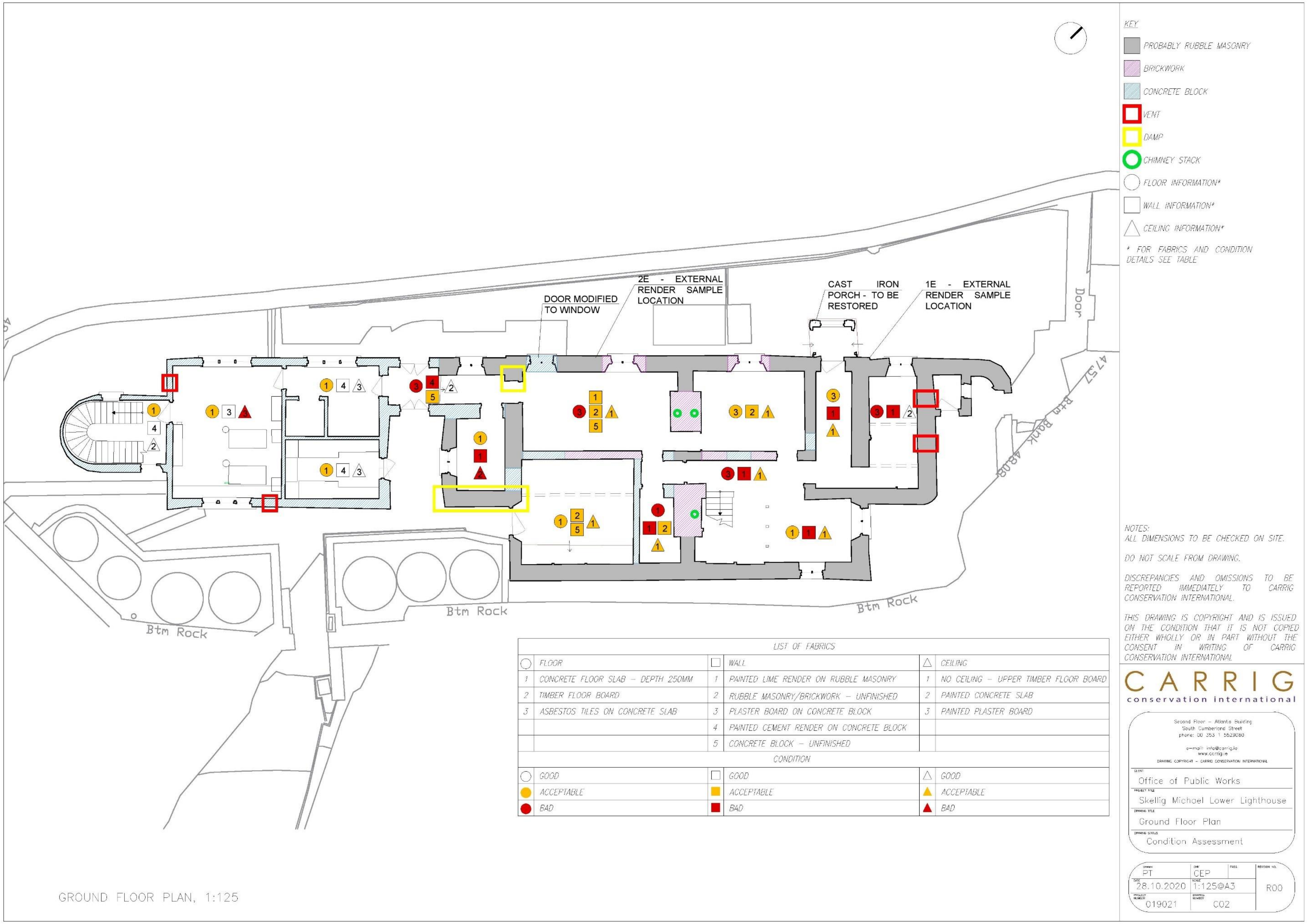
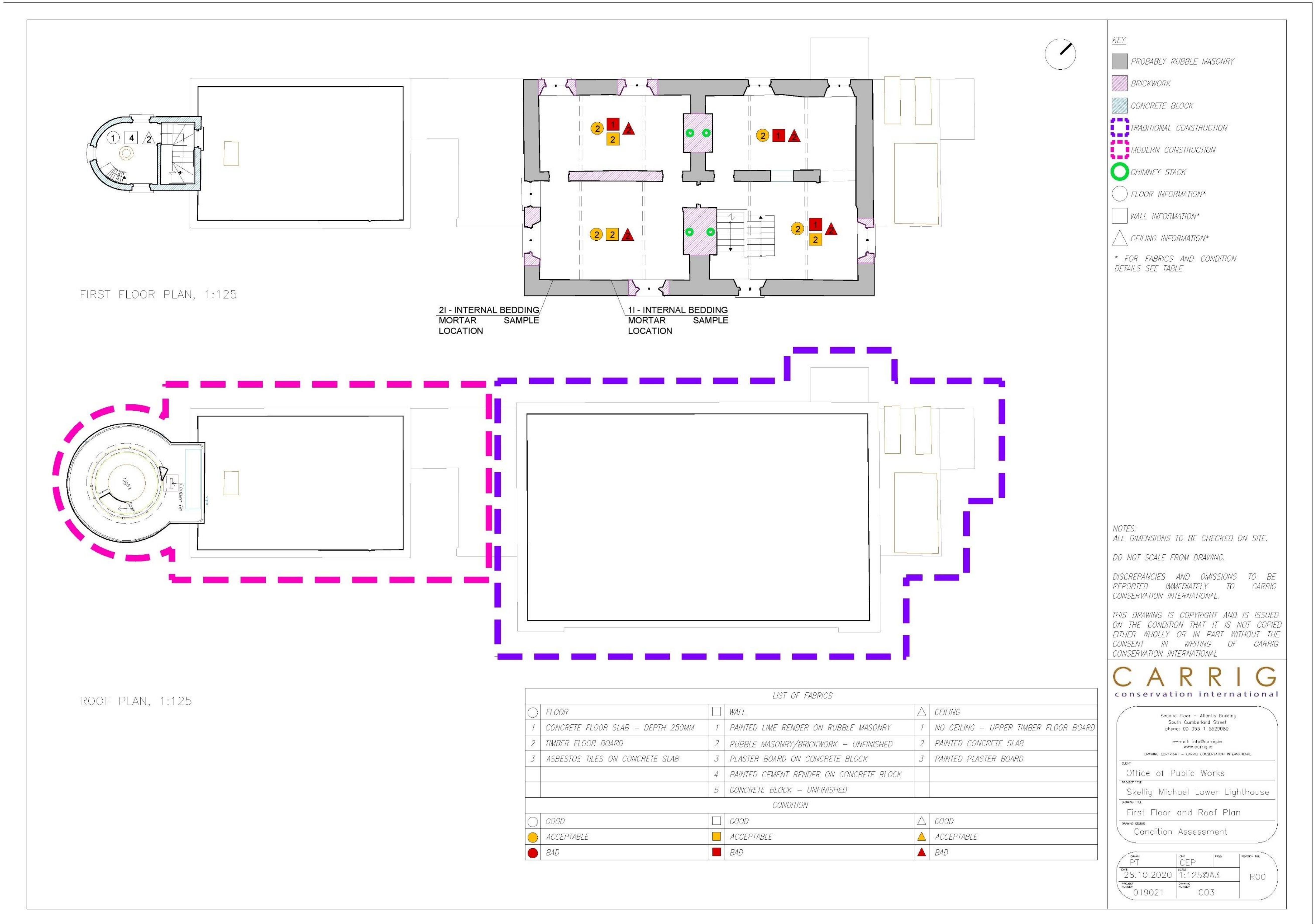


Figure 11. Condition Assessment - Ground Floor Plan (Carrig, 2020).



LIST OF FABRICS					
○	FLOOR	□	WALL	△	CEILING
1	CONCRETE FLOOR SLAB - DEPTH 250MM	1	PAINTED LIME RENDER ON RUBBLE MASONRY	1	NO CEILING - UPPER TIMBER FLOOR BOARD
2	TIMBER FLOOR BOARD	2	RUBBLE MASONRY/BRICKWORK - UNFINISHED	2	PAINTED CONCRETE SLAB
3	ASBESTOS TILES ON CONCRETE SLAB	3	PLASTER BOARD ON CONCRETE BLOCK	3	PAINTED PLASTER BOARD
		4	PAINTED CEMENT RENDER ON CONCRETE BLOCK		
		5	CONCRETE BLOCK - UNFINISHED		
CONDITION					
○	GOOD	□	GOOD	△	GOOD
● (orange)	ACCEPTABLE	■ (orange)	ACCEPTABLE	▲ (orange)	ACCEPTABLE
● (red)	BAD	■ (red)	BAD	▲ (red)	BAD

Figure 12. Condition Assessment – First Floor Plan (Carrig, 2020).

7 Assessment of Adaptive Capacity

7.1 Best Practice Guidance

The following standards and best practice guidance have been reviewed to determine appropriate measures to improve the thermal performance of the Lower Lighthouse as much as possible without compromising the material, historic or aesthetic characteristics of the building. The final Fabric Retrofit Strategy gives preference to low-risk, high-impact measures that are suitable for traditional buildings and historic structures.

7.1.1 I.S. EN 16883:2017 Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings

European Standard 16883 *Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings* was approved at the European level in February 2017 and has since been transcribed into Irish Standards (European Committee for Standarisation, 2017). The standard is designed to be used by building professionals to improve energy performance and to lower the greenhouse gas emissions from historic buildings of all ages and types regardless of protected status. The standard presents a normative working procedure to assist designers in finding the most appropriate sustainability measures for each individual building based on investigation, analysis and documentation of the building, including its heritage significance. The standard does not presuppose that all historic buildings need sustainability improvements.

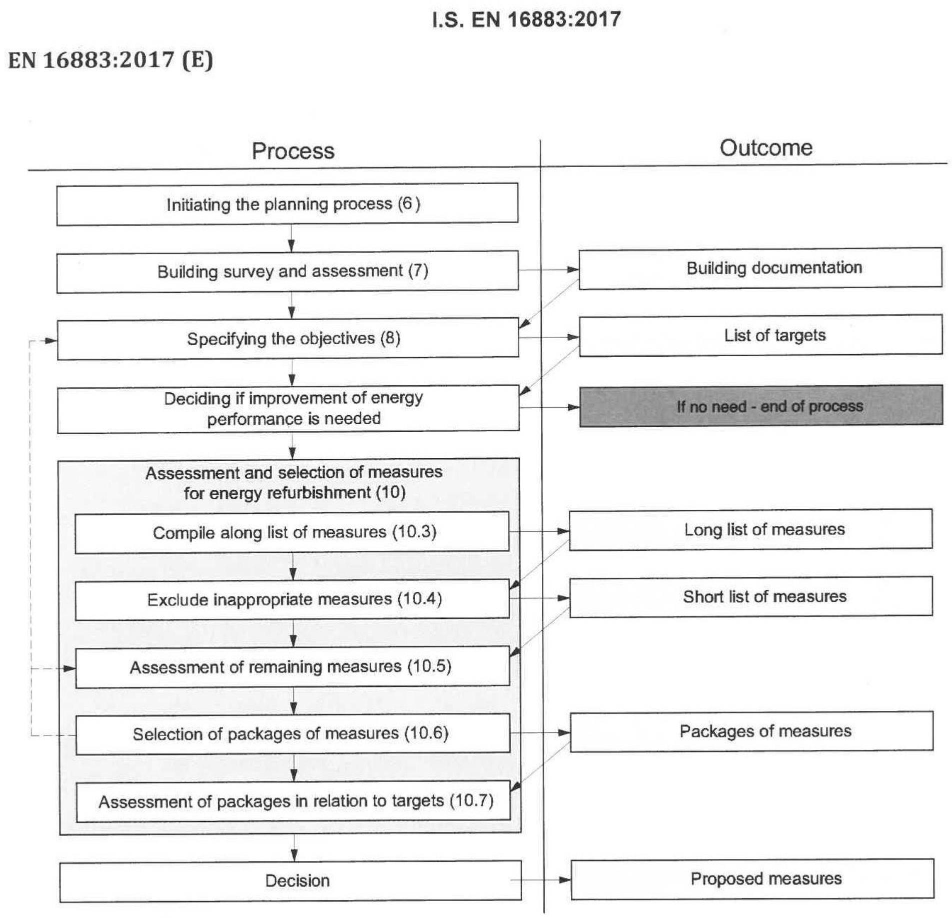


Figure 13. EN 16883 flow chart showing the proposed procedure to determine appropriate retrofit options (European Committee for Standarisation, 2017).

7.1.2 STBA Responsible Retrofit Guidance Wheel

The Sustainable Traditional Buildings Alliance (STBA) is an independent, not-for-profit organisation established in 2012 to inform policy and develop guidance and training to limit the negative impacts on traditional buildings and maximise benefits to the building and homeowners when maintenance, repair and energy renovation works are being undertaken. The STBA has also published a number of advisory papers as part of their *Responsible Retrofit* guidance series (May and Griffiths, 2015; May and Rye, 2012; STBA, 2016).

The Responsible Retrofit Guidance Wheel (Figure 14) developed by the STBA is another helpful decision-making tool which was used to verify the recommended retrofit measures for the Lower Lighthouse (STBA, 2017).

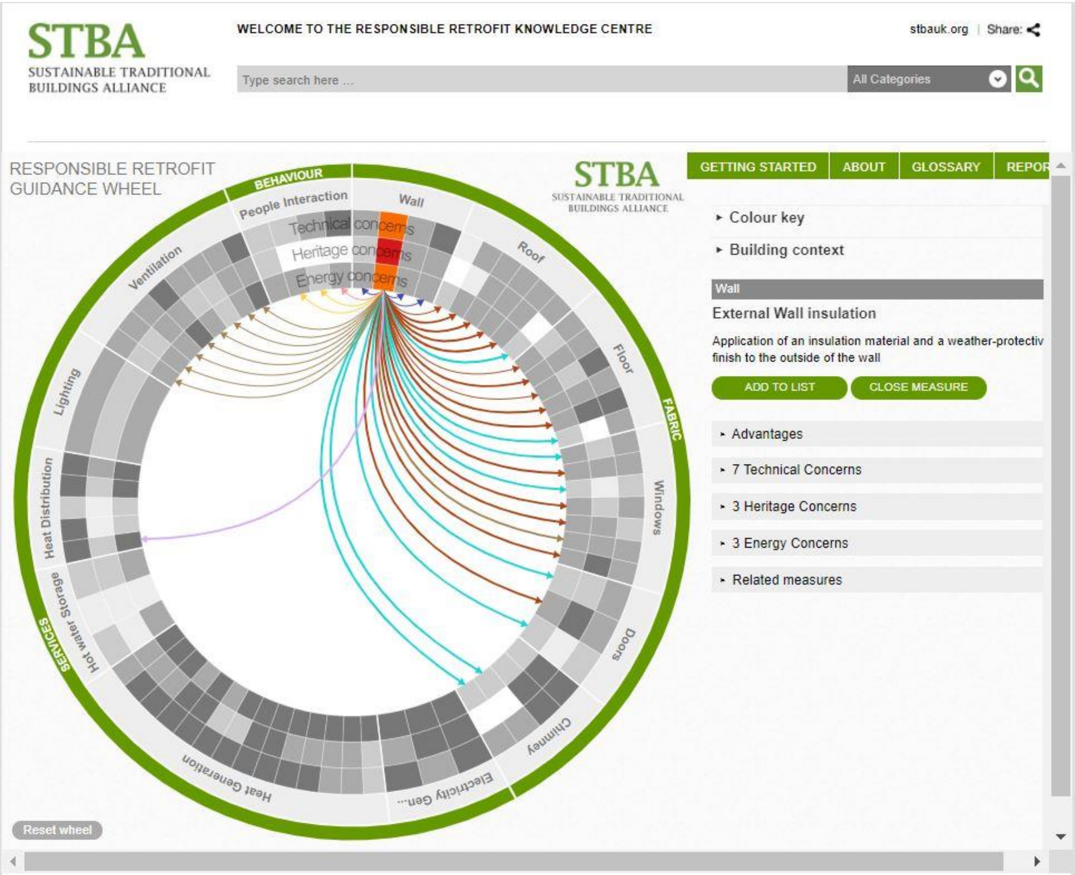


Figure 14. The STBA Responsible Retrofit Guidance Wheel developed to inform the decision making process (STBA, 2017).

7.1.3 Historic Environment Scotland

Historic Environment Scotland (HES) has led the way in producing technical guidance on the refurbishment and retrofit of traditional and historic buildings. Due to the similarities between the Irish and Scottish climates and building traditions, much of the HES recommended guidance is applicable to the Irish context. The HES Technical Papers, Technical Advice Notes and Refurbishment Case Studies are written with the building and conservation professional in mind and therefore provide a high level of detail on complex matters.

7.1.4 Historic England

Historic England (HE) has also published a number of energy efficiency technical reports under their Research Reports series and more general guidance notes under their Energy Efficiency and Historic Buildings series. The current focus of their energy efficiency research and guidance can be summarised in five categories:

- thermal performance of traditional buildings;
- moisture accumulation in building fabric due to energy efficiency measures;
- numerical modelling of hygrothermal behaviour of building fabric as a risk assessment tool;
- ‘whole building’ approach to energy saving in historic buildings; and
- the SPAB building performance survey.

7.1.5 Additional Resources

Sustainable Renovation: Improving Homes for Energy, Health and Environment (Morgan, 2018) provides principles and details for building practitioners working with the energy upgrade of existing domestic buildings.

Thermal Insulation Materials for Building Applications (Latif, Bevan and Woolley, 2019) is a valuable independent review of the performance and environmental impact of numerous insulation products on the market.

7.2 Calculated U-value for External Masonry Walls

Prior to specifying thermal upgrades to solid masonry walls, it is important to understand how well they are currently retaining heat. To do so, the u-value of a first floor wall on the northwestern elevation of the Lower Lighthouse has been calculated based on the material properties and wall build up. Without coring into the wall, it appears to be primarily composed of local slate and lime mortar. The full depth of the wall is approximately 600mm, including the external lime render (approx. 40mm). The internal plaster has been removed, but it has been assumed that its replacement would bring the depth of the wall up to 640mm.

Figure 15. The calculated u-value is based on the above wall, which is primarily composed of slate and lime mortar to a depth of approximately 600 mm (OPW, 2020).

To calculate the u-value of this wall, the methodology specified in I.S. EN ISO 6946:2017 *Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods* has been followed (European Committee for Standardisation, 2017). This method assumes steady-state conditions independent of actual conditions (e.g. indoor temperature or the effect of wind or solar radiation).

The following assumptions have been made for this wall:

- Where a range of R-values is provided for materials, a median value was used.
- The approximate proportion of stone to mortar has been assumed to be 60% to 40%. The stone and mortar have been calculated as two separate layers (i.e. the depth of stone is calculated at 60% of 560mm and the depth of mortar is calculated at 40% of 560mm) (Baker, 2011).
- The internal walls will be re-rendered with 40mm of lime plaster.

First, the thermal resistance of each building materials must be calculated using the following formula:

$$R = d/\lambda$$

Where

R = thermal resistance in m^2K/W

d = thickness of material layer in the component in m

λ = design thermal conductivity of the material in W/(mK)

So, the thermal resistance of the four materials are as follows:

External lime render (40mm) = 0.04/0.68 = 0.059

Slate (60% of 560mm) = 0.336/1.442 = 0.233

Lime Mortar (40% of 560mm) = 0.224/0.68 = 0.329

Next, the thermal transmittance (u-value) is calculated as follows:

$U = 1/R_{tot}$

Where

U = thermal transmittance in $W/(m^2K)$

R_{tot} = total thermal resistance in m^2K/W

So, the calculated u-value of the existing wall is:

Existing U-value = 1/(0.059 + 0.233 + 0.329) = **1.61 W/(m²K)**

Once the internal walls are replastered with lime (40mm), we could expect the u-value to improve to:

Internal lime plaster (40mm) = 0.04/0.68 = 0.059

Improved U-value 1 = 1/(0.059 + 0.233 + 0.329 + 0.059) = **1.47 W/(m²K)**

If the external lime render were replaced by a moisture permeable insulating lime render (λ = 0.086 W/(mK)), we could expect the u-value to improve to:

Insulating lime render (40mm) = 0.04/0.080 = 0.500

Improved U-value 2 = 1/(0.500 + 0.233 + 0.329 + 0.059) = **0.89 W/(m²K)**

An external insulating lime render would therefore improve the existing u-value by approximately 55%.

As u-value calculations are based on approximate thermal conductivity values for each material (many of which are not local varieties in Ireland), a much more precise measurement can be achieved through in-situ u-value tests. These are typically run for a minimum of 1 week per test site to ensure the readings are accurate.

Further recommendations to improve the thermal efficiency of the building are provided under Section 8.

7.3 Environmental Considerations for Insulation Materials

Modern insulations include mineral wool, glass wool, fully bonded polyurethane (PUR) / polyisocyanurate (PIR), expanded polystyrene (EPS) and aerogel. Natural insulations include hemp fibre, hemp lime, sheep's wool and wood fibre. While thermal conductivity is often the only factor considered when specifying an insulation type for the thermal upgrade of a building, other factors such as the vapour diffusion resistance factor, embodied energy, global warming potential, toxicity and biodegradability should also be taken into consideration (Table 3). EPS and PUR/PIR have a high vapour diffusion resistance factor, meaning they inhibit moisture from moving through them and will instead force the moisture to move through porous traditional materials and cause their expediated decay. For this reason, these should not be used in traditional buildings.

Table 3. Environmental attributes of common insulation materials (Latif, Bevan and Woolley, 2019).

Insulation	Thermal Conductivity (W/mK)	Vapour Diffusion Resistance Factor (μ)	Fire Rating	Toxicity	Biodegradability	Embodied Energy (MJ/kg)	Global Warming Potential (kg CO_2 eq.)
PUR/PIR	0.021 - 0.025	50	E (combustible)	Fatally toxic when burned (Grenfell Tower)	No Requires >1000 years to degrade	104.03	116 - 164
EPS	0.030 - 0.045	20-100	E/F	Endocrine disrupter and possible human carcinogen	No Requires >100 years to degrade	104.03	82
Mineral Wool	0.035 - 0.047	1-2	A1 (non-combustible)	Residual formaldehyde emissions	No	16.6	44
Glass Wool	0.035-0.047	1-2	A1	Residual formaldehyde emissions	No	28	44
Hemp Fibre	0.038-0.044	1.5-2.7	E or F	No known negative health impacts	Yes	10	14.7
Hemp Lime	0.055-0.12	1-3	1 h BS EN 1365;1:1999	No known negative health impacts	Yes	1-4	-60 to -70[1]
Sheep's Wool	0.038-0.045	1-5	B2-E	Sheep's wool dust may irritate eyes and airways, but it can absorb VOCs	Yes	6-20	0
Wood Fibre	0.040-0.090	5-10	E (B1-B2 in DIN 4102)	No known negative health impacts and may contribute to healthier indoor environments by regulating relative humidity and temperature	Yes	10	-181[2]
Aerogel	0.012-0.021	5	A2, C	Aerogel dust may irritate skin, eyes, mucous membranes and upper respiratory tract	No	84	86

[1] Hemp is considered a carbon neutral or carbon negative product as more carbon is sequestered by the hemp plants than is emitted during the production of the insulation product. Hemp lime contains 110-165 kg of sequestered carbon per unit volume, resulting in a negative GWP value.

[2] Like hemp, wood fibre products are considered carbon neutral or carbon negative because trees sequester more carbon during their life than is emitted during the production of the insulation product.

7.4 Retrofit Impact Assessment

The following Retrofit Impact Assessment has been adapted from the format recommended in I.S. EN 16883:2017. The potential retrofit measures were reviewed against their technical compatibility, impact on heritage significance and energy saving potential. Any measures presenting high risks (red) from a technical or heritage perspective will not be considered in the final retrofit specifications regardless of the potential energy efficiency benefits they provide.

The assessment of each retrofit measure has been based on best practice guidance, the findings from the site visit and Carrig's professional experience with historic and traditional buildings.

Note: The technical risk assumes that the appropriate materials and methods according to best practice guidance will be followed. The impact on heritage significance is based on the existing condition of the building.

	Assessment Scale		
Benefit	Low	Medium	High
Risk / Impact	Low	Medium	High

Table 4. Assessment of potential benefits and risks/impacts posed by short-listed retrofit measures for the Skellig Michael Lower Lighthouse (Carrig, 2020).

Concern	Assessment Criterion	Installation of internal shutters	Insulate internal shutters	Installation of thermal curtains	Draughtproof windows & doors	Install internal secondary glazing	Replace existing windows with timber double-glazed units	Replace concrete floor with insulated limecrete floor (GF)	Install underfloor heating with an insulated limecrete floor	Install underfloor heating with a new concrete floor	External insulating lime render	Internal lime plaster	Internal insulating lime plaster	External warm roof insulation (flat roof retained)	French drain around building perimeter
Technical / Material	**Risk** (condensation, thermal bridging, etc.)														
Heritage Significance	**Impact** (material, aesthetic, spatial, historical, etc.)														
Energy Efficiency	**Benefit** (level of improvement)														

7.5 Recommended Surveys

As part of the technical discussion, Carrig will meet with the OPW to discuss our findings and advise on the potential energy surveys that would provide useful data to confirm the adaptation capacity of the building and the suitability of the identified retrofit solutions. At this meeting, Carrig will provide an overview of each survey method and associated costs so that the OPW can make an informed decision based on the retrofit options appropriate for the Lower Lighthouse. Energy survey options may include:

Calculation of Theoretical U-values for Walls, Roof, Ground Floor and Window

A better understanding of the thermal performance of the external envelop of the building can be gained by calculating the theoretical u-values for the different wall types, foundations, the roof and windows. Further opening up works may be required to determine the build-up and thickness of each element.

In-situ U-value Measurements

While more costly to carry out, in-situ u-value measurements will provide more accurate u-value measurements of representative wall types found throughout the building. U-value measurements must be compliant with ISO 9869-1:2014 to be used in NEAP to ascertain a more representative BER for the building.

Indoor Air Quality Monitoring

Indoor Air Quality monitoring can be conducted in a variety of internal spaces for a duration of approximately 1 month to inform the development of a ventilation strategy for the building. IAQ monitoring will measure temperature and relative humidity, as well as a number of airborne pollutants.

Porosity Testing

Karsten tubes can be used to measure the absorptivity of the external wall fabric. This data would then be input into WUFI to conduct a condensation risk assessment for the building and to determine if any thermal upgrades (i.e. solid wall insulation) to the building are likely to cause unacceptable levels of moisture retention.

Condensation Risk Assessment

Data from the previously mentioned surveys can be used to assess the hygrothermal risks associated with the potential thermal upgrade options for the building fabric using WUFI. Opening up works will be required in addition to the previously listed surveys to ensure a thorough understanding of the building.

Thermal Bridge Analysis

Data from the previously mentioned surveys can be used to assess the risk of thermal bridging posed by the potential thermal upgrade options for the building. Detailed drawings and specifications will be required for this assessment.

Interstitial Moisture Monitoring

If solid wall insulation is applied, it is recommended to monitor the interstitial moisture levels for at least 1 year but preferably for to 2-3 years. This will provide useful data on the thermal performance of the external walls and will alert to any potential moisture related issues at the earliest instance.

Note: The results of the petrographic analysis of select building material samples can be found in the *Lab Report on Geological Analysis of 5 Rock, Mortar and Render Samples*. That report should be read in tandem with this strategy.

8 Fabric Retrofit Strategy

The following recommendations are based on discussions with the OPW project team, the condition assessment, best practice guidance and the retrofit impact assessment.

Each proposed intervention will need to be reviewed with the Project Manager and appointed design team prior to finalising the documentation for cost analysis, planning permission and tendering for construction.

In general, all insulation and surface materials (paint, flooring, etc.) must be low carbon, vapour permeable and historically compatible with the existing building. Great care should be taken to allow water and vapour to be naturally removed from the property as soon as possible to avoid issues with damp and interstitial condensation. Low carbon materials and processes should be prioritised.

8.1 Preparations

8.1.1 External Render

A thorough condition assessment of all external lime render should be done and any cement render should be removed from the masonry walls down to the substrate (cement render may be retained on the modern concrete block walls). Repairs to the lime render should respect the two aggregates identified in the geological lab analysis report, both of which should be available in west County Kerry.

While the render is off, any cement pointing and/or open joints should be raked out and filled with lime mortar.

If the building is to be re-rendered in an insulating lime render, then all existing render (lime and cement) must be removed down to the substrate. This should be done during the spring to allow the building fabric to dry out over the summer prior to the application of new lime render. Repairs to the masonry joints should be conducted as above prior to the application of insulating lime render.

8.1.2 Ground Water Control

A damp wall is approximately 30% less thermally efficient than a dry wall, so steps should be taken to direct rain and ground water away from the base of the building.

All concrete and tarmac abutting the building should be removed and replaced with a more permeable surface to allow a more natural absorption and distribution of rainwater around the site. A French drain system should be installed around the external perimeter of the building prior to erecting the scaffold. Care should be taken to not undermine the foundations of the building.

8.2 External Works

8.2.1 Roof

Approximately 25% of heat is lost through the roof of an average building and it is often one of the most cost-effective and beneficial areas of a building to improve.

As it is the intention of the OPW to retain the flat concrete roof, the roof should first be thoroughly surveyed above and below for cracks and evidence of water ingress and or steel corrosion (all existing coverings will likely need to be removed). It is understood that repair works have been undertaken in recent times, however the internal spaces should be monitored during wet months to ensure no further water ingress is occurring.

If the finished incline of the existing roof is not at least 1 in 80 (or 1°), the new surface will need to be laid to ensure water is carried off the roof. Given the particularly wet and wild weather of the region, it would be advised to increase the incline to 1 in 60. Drainage routes to rainwater goods must also be checked to ensure no pooling is occurring at roof level or ground level.

It is recommended to insulate the roof deck using a 'warm roof' method, i.e. to insulate above the concrete roof deck to keep it warmer (Figure 16). The 'cold roof' insulation method, whereby insulation is installed to the underside internal face of the ceiling has been largely discontinued and has been banned in Scotland due to its propensity to cause moisture related issues due to inefficient ventilation. Using the 'warm roof' method, a vapour control layer

(VCL) should be installed below the insulation and a waterproof layer should be installed above to minimise water ingress. It is essential that no piercings are made through either the VCL or waterproof membranes, so great care will need to be taken if rooftop solar panels are to be installed above the finishing layer.

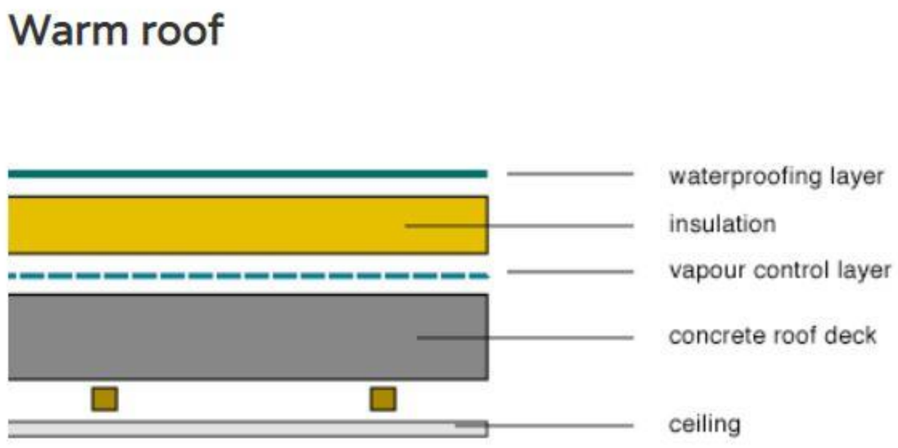


Figure 16. Build-up of the 'warm roof' insulation method for flat concrete roofs (Greenspec, 2020).

Typical insulations used for the warm roof method include mineral wool slabs, fully bonded polyurethane (PUR) / polyisocyanurate (PIR) or expanded polystyrene (EPS). All of these insulations have a negligible absorption of moisture at 98% humidity, but whichever insulation is used, it must not be susceptible to moisture. From an environmental point of view, mineral wool is the best choice as it has significantly lower levels of embodied energy and global warming potential, but it also has an A1 fire rating and low toxicity (see Table 3).

It is essential that the underside of the finishing roof covering is ventilated. If lead is to be used as a finishing covering, good quality softwood decking should be used below to help buffer moisture levels. Plywood should not be used as the acidic glues can deteriorate the lead from below. Copper and stainless steel are also extremely durable and while the copper will gain a nice blue-green patina due to oxidisation, the stainless steel can be treated with a 'terne-coating' finish to dull its appearance to a matt-grey similar to weathered lead. Zinc and aluminium have poor durability and would not be recommended, especially due to the location and access related issues for the Lower Lighthouse.

As shown in Figure 9, the steel mesh and I-beam supports will need to be treated to halt corrosion. Carrig will review the recommendations for the treatment of corroded steel from the appointed engineers once these are received.

8.2.2 Rainwater Goods

Consideration should be given to increasing or oversizing the gutters and downpipes to future-proof against increased rainfall due to climate change. According to Climate Ireland predictions, average rainfall has already increased by 5% since the mid-20th century and is expected to increase by a further 30% during winter months by 2060.

All existing rainwater drains should be checked to ensure they are clear and are dispersing water a safe distance from the building. To determine the requirements of replacement rainwater goods, the performance of existing rainwater goods should first be reviewed during heavy rainfall to see if they are coping with the runoff. Replacement rainwater goods should then be designed to cope with a 30% increase to the average peak rainfall intensity for this region in winter months. Replacement rainwater goods are to be designed and manufactured in cast iron.

Rainwater harvesting should be considered with a view to producing a grey water solution.

8.2.3 External Walls

To improve the operating efficiency of the Air Source Heat Pump (ASHP) proposed by ARUP, it will be necessary to improve the heat retention of the walls and the building in general. As calculated in Section 7.2, the existing u-value of the external masonry walls could be improved by approximately 55% from 1.61 W/(m^2K) to 0.89 W/(m^2K) if an external insulating render were applied.

Lime-based insulating renders may contain either hemp or cork, must be suitable for outdoor applications and must not have any cement content. It is recommended that the external render not exceed 50mm in depth to allow moisture within the wall to evaporate outward as quickly as possible. While a number of insulating lime render products exist, Diasen Diathonite Deumix+ has been designed specifically for wet masonry and environments. It is a dehumidifying render with excellent water repellent properties and an anti-saline regularization layer. As with other lime renders and plasters, it is highly breathable and allows excess moisture within the wall to evaporate. Lime-based render is also a natural, environmentally friendly, low carbon product that reabsorbs carbon from the atmosphere while it cures.

The insulating render should be finished with a product like Argacem HP to provide a breathable moisture barrier (5mm skim coat). If the finished external render is to be painted, a diffusion open mineral based paint must be used, such as Keim Mineral Paints, Auro Natural Paints or similar. Regular water repellent paints will trap moisture and will inhibit the insulating lime render from functioning as it should.

Evidence was found during the site visit that the front (northwest) elevation of the building may have originally been clad with slates as a weatherproofing measure. It may be an option to reintroduce slate cladding to the outside of the Diathonite render on the most exposed elevations of the building, but a condensation risk assessment should be undertaken prior to its installation.

It is highly recommended that a condensation risk assessment and thermal bridge analysis be undertaken for all major junctions prior to the installation of thermal upgrades to ensure that no cold spots or moisture related issues are created by the solid wall insulation (see Section 7.5 for details).

8.3 Internal Works

8.3.1 Ground Floor

Non-breathable floors such as concrete within vapour-permeable stone walls can cause moisture-related issues by diverting excess ground moisture up the walls leading to issues with ‘rising damp’ (Figure 17).

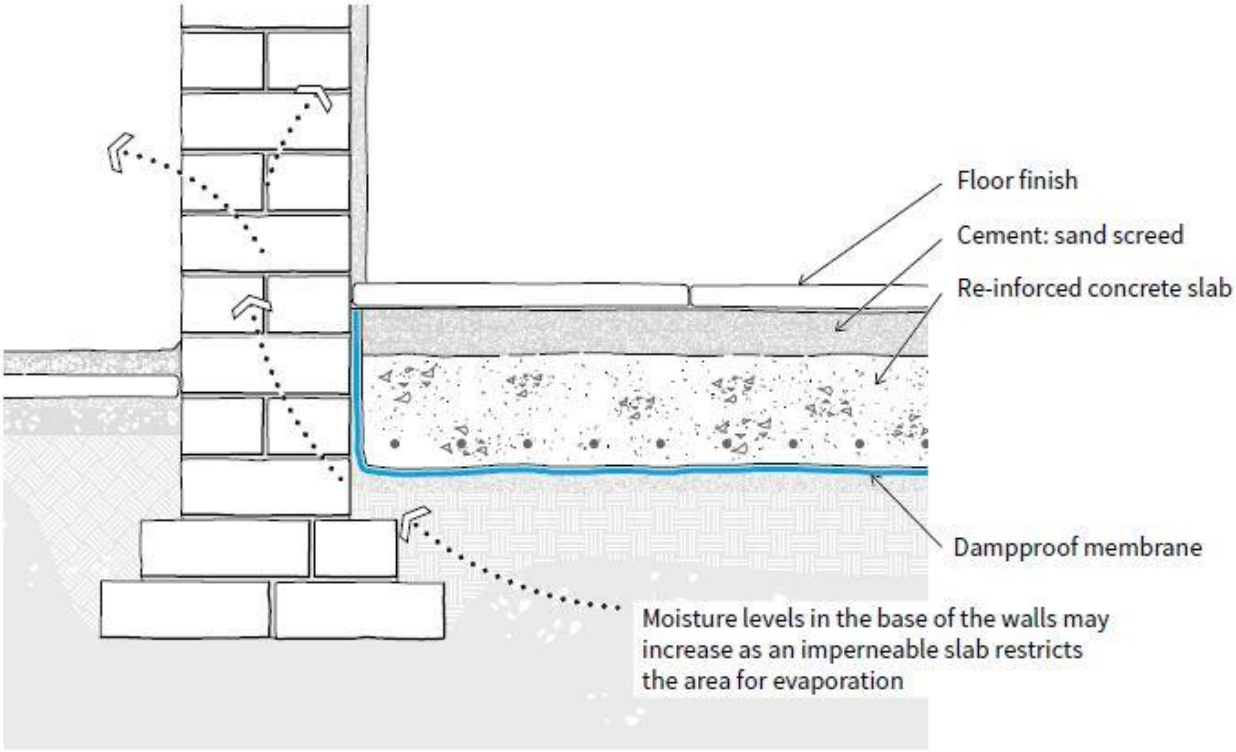


Figure 17. Moisture movement in a traditionally constructed building after the installation of a concrete floor and damp-proof membrane (Pickles, 2016).

It is therefore recommended to remove the existing solid concrete floors and install an insulated limecrete floor with underfloor heating to be supplied by the ASHP. Recycled foam glass or expanded clay aggregate should be used as a loose-lay insulating layer beneath the limecrete, which will also inhibit ground water penetration.

If underfloor heating is to be installed, it should be laid upon a geogrid above the insulating aggregate and below the limecrete screed. This build-up provides a high degree of insulation while maintaining the breathability that is essential in all traditionally constructed buildings (Figure 18). A 40mm thick cork edge board may be installed along the perimeter of the floor between the lime screed and external walls for extra insulation.

The top floor finish must also be breathable, e.g. stone, wood or non-glazed tile using a breathable adhesive. Issues with ground source moisture can be further minimised with the installation of a French drain around the perimeter of the property.

If high levels of radon are present on the island, a radon barrier should be installed below the geotextile layer.

Figure 18. Insulated limecrete floor with underfloor heating (Tŷ-Mawr Lime Ltd., 2020).

Aside from the incompatibility of concrete with traditional building materials and moisture movement processes, concrete is a high carbon material that should be used as little as possible. The production of cement accounts for 4-8% of all global CO_2 emissions and the production of one tonne of cement emits 780 kg of CO_2. As a major contributor to climate change, it is therefore important to use more sustainable alternatives whenever possible. The production of hydraulic lime also produces carbon emissions, however lime reabsorbs CO_2 as it hardens, reducing its overall global warming impact. At the end of its useful life, limecrete can also be recycled and reused, whereas concrete will likely end up in the landfill.

8.3.2 Internal Walls

It is understood that all internal walls have been stripped of their plaster or coverings. Damp walls should be left to dry out over the summer months before the new lime plaster is applied. The new lime plaster should be applied to the same depth as the original (approx. 30mm). Vapour barriers or drylining of any sort ***must not be used*** and an airtightness layer is not required with wet plaster.

While the plaster is off, the wall structure should be inspected for voids and repaired where necessary with lime mortar.

Given that an insulating lime render has been recommended for the exterior of the building, it is not recommended to insulate the internal face of the walls as well. The use of a regular lime plaster internally will allow moisture to be pushed out through the walls over the autumn, winter and spring heating seasons, which will maintain a healthy moisture balance internally and within the building fabric.

8.3.3 Windows & Doors

Heat loss through windows happens in three forms: radiant (through the glazing), conductive (through the frames) and convective (through draughts).

It is recommended that the historic windows be restored, draughtproofed and further insulated with low-profile removeable secondary glazing. The secondary glazing can be removed and safely stored away during summer months when less thermal insulation and more natural ventilation is needed.

As all window boxes appear to have been removed, the insulating lime plaster should be applied around the window reveals to reduce thermal bridging. Properly applied wet plaster should provide adequate draughtproofing around windows, but additional airtightness tapes and soft breathable insulations (e.g. hemp fibre, sheep's wool or similar) can also be used behind the new window box to provide added thermal benefits and to reduce uncontrolled draughts.

Exterior vapour-permeable timber paints should be used to avoid trapping moisture in the timber frames, which will expediate rot.

Internal thermal curtains should be installed to further improve the retention of heat at night. Timber shutters could also be installed externally to protect the windows and building during the off-season when the building is not inhabited.

All historic doors and frames should be retained and repaired. External doors should be draughtproofed and if they must be replaced, the replacements should be stylistically similar insulated doors that are able to withstand the weather. If the internal doors must be replaced, they should be replaced with stylistically similar timber doors.

New doors should be assessed for full compliance with building and fire regulations and be historically appropriate for the building. The selection of doors with a low carbon footprint and low U-values should be the priority.

8.4 Additional Considerations

8.4.1 Heritage Conservation

No works should be undertaken that will harm or devalue the historic qualities and heritage value of the building and site. The intent should be to reverse previous inappropriate alterations while improving the energy and thermal performance of the building. Preference should be given to reversible measures.

8.4.2 Airtightness

Airtightness is a relatively new consideration in historic or traditional buildings, however it is extremely important to address in order to improve the energy efficiency of the building. It is estimated that 40% of heat loss in older buildings is due to uncontrolled draughts.

Improving the airtightness of the building will lower operational heating requirements and in turn, carbon emissions. It is therefore one of the most cost-effective ways to improve the energy efficiency of older buildings.

Airtightness membranes and tapes for traditional buildings *must* be moisture permeable. Special consideration should be given to the routing and re-routing of services to avoid unnecessary holes in the building fabric and airtightness layers. Lime plasters and renders (insulating or traditional) naturally reduce draughts around windows and doors so no additional airtightness tapes or membranes should be required with their application.

8.4.3 Ventilation

Improved airtightness *must* correspond with an adequate ventilation strategy in order to maintain safe moisture levels and a healthy indoor environment. With increased insulation and airtightness, trickle vents may no longer ensure enough air movement, particularly in wet rooms like kitchens and bathrooms.

Indoor Air Quality (IAQ) monitoring should be undertaken in a variety of occupied spaces for a period of 1 month to determine the ventilation requirements for the building. IAQ monitors collect data on internal temperatures, relative humidity as well as a number of airborne toxins.

Strategically placed demand controlled extraction vents which are triggered by excess humidity may be an option for wet rooms (W.C., kitchens, laundry rooms, etc.), but ventilation requirements will be contingent on the number of people expected to use the building on any given day, indoor air pollutants and moisture levels. For larger buildings, a centralised heat recovery ventilation system may be more suitable to remove unsafe levels of toxins, CO_2 and humidity. Mechanical ventilation units should operate at less than 30db to avoid the impression that they are excessively noisy. The final ventilation strategy will need to be very carefully worked out with a specialist in this area.

If natural ventilation is deemed sufficient, adequate ventilation can be maintained through the use of trickle vents and windows. Building occupants will need to be instructed to diligently manage moisture levels within the building by opening windows when cooking or showering. As there will likely be more than one person sleeping in each bedroom, it is essential that adequate ventilation is maintained and occupants may need to be instructed against blocking up trickle vents.

8.4.4 Energy Sources

Carrig have reviewed the recommendations developed by ARUP for the Lower Lighthouse and are in agreeance with the strategy. Below are a few additional comments to be considered by the OPW design team.

New high temperature air-to-water heat pumps were released in early 2020 by Daikin, which are suitable for historic buildings and may be more efficient in this instance. However, prior to their installation, the thermal efficiency of the building should be improved as much as possible to ensure the heat pump operates efficiently.

As the chimneys have all been blocked up by concrete, it will not be possible to supplement the underfloor heating and low temperature radiators with wood burning stoves. It will likely be necessary to provide some form of additional top-up heating in order to keep the building fabric and internal environment dry as well as to maintain a comfortable indoor temperature for occupants during particularly cold days in the spring and autumn.

Lighting is to be carefully planned to suit the specific purpose of each space. All lighting should use low-energy LED bulbs, which use approximately $1/6^{th}$ of the energy required by traditional incandescent bulbs. All new wiring needs to be well thought out and installed prior to final internal finishes.

All appliances should be energy efficient.

8.4.5 Life Cycle Assessment

To fully understand the environmental impacts of the refurbishment works, it is recommended that a life cycle assessment be undertaken at concept design stage to assess the environmental impacts of the materials, systems and works specified by the design team. Lower carbon options could be found at this stage for any materials, systems or works that will result in particularly or unnecessarily high embodied and operational carbon emissions.

Detailed drawings, specifications and a full bill of quantities will be required for life cycle assessment.

8.4.6 User Behaviour

Building users should be made aware of how their behaviour impacts the energy consumption and internal environment of the building. Building users and occupants should be supplied with an easy-to-follow user manual that describes how to manage moisture and energy use in the most sustainable manner.

8.4.7 Site Management

Depending on the future use of the building, consideration may need to be given to the development of a facility management file so that none of the low-energy or low-carbon interventions are interfered with or mistakenly changed in the short, medium or long term.

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