



Study of environmental and energy performance of vegetative roofs and assessment of their impacts in terms of rainwater management

Makram El Bachawati

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UNIVERSITY of LA ROCHELLE, FRANCE –UFR Science and technology
Laboratory of Engineering Science for Environment (LaSIE) UMR CNRS 7356

and

UNIVERSITY of BALAMAND, LEBANON – Faculty of Engineering
Chemical Engineering Department

**STUDY OF ENVIRONMENTAL AND ENERGY PERFORMANCE OF
VEGETATIVE ROOFS AND ASSESSMENT OF THEIR IMPACTS IN
TERMS OF RAINWATER MANAGEMENT**

presented by

MAKRAM EL BACHAWATI

A thesis submitted to the doctoral school in Materials, Mechanics, Energy and Aerospace
Sciences and Engineering and to the Department of Chemical Engineering in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

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and

UNIVERSITY of BALAMAND, LEBANON

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This thesis entitled:

**STUDY OF ENVIRONMENTAL AND ENERGY PERFORMANCE OF
VEGETATIVE ROOFS AND ASSESSMENT OF THEIR IMPACTS IN TERMS
OF RAINWATER MANAGEMENT**

Presented by: EL BACHAWATI Makram

In order to obtain the degree of: Philosophiae Doctor

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DEDICATION

I dedicate this thesis

to my wife and daughter,

to my mom, my dad, and my brother.

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Although only my name is shown at the cover page, but several people assisted me during this journey. I thank them all with my heart.

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ABSTRACT

Vegetative roofs (VRs), also termed as garden roofs, are "systems that promote the growth of plants on rooftops". VRs can be classified into two types: Extensive and Intensive. The main differences between the two are the type of vegetation, the depth of the substrate, and the load especially when they are saturated with water. Extensive Green Roofs (EGRs) are characterized by a thin soil layer (< 200 mm), while Intensive Green Roofs (IGRs) have a thicker growing medium (> 200 mm).

Internationally, VRs have gained popularity because of their advantages from an environmental, economic and energetic perspective. In particular, VRs could improve air and water quality, reduce temperature fluctuations, mitigate urban heat island effect, decrease noise pollution, and provide food and a safe habitat for many species.

In Lebanon, a country in the Middle East, only two EGRs have been installed so far. The installation of VRs in Lebanon could be an interesting option, as the country lacks a clear sustainability plan as well as an infrastructure update and management, leading to road flooding in urban areas, amongst other things such as an electricity deficit and a continuous need for heating/cooling systems.

This research aims to achieve the following objectives:

1. Determine and compare the potential environmental impacts of traditional gravel ballasted roofs (TGBRs), white reflective roofs (WRRs), and VRs;
2. Evaluate and compare the energy performance and the heating/cooling demand of TGBRs and EGRs;
3. Determine and compare the water management potential and the runoff dynamics of TGBRs and EGRs.

The first objective was covered by performing a cradle-to-gate Life Cycle Assessment (LCA) on a real EGR of 834m^2 installed at the Central bank of Lebanon and on three fictitious roofs of the same area: of TGBRs, WRRs, and IGRs. Life Cycle Assessment is a tool to evaluate the

environmental impacts of a product, process, or service from the raw material extraction to the end-of-life. The functional unit used was: “The construction and installation of a roofing system to cover a surface of 834m² for 45 years”. The system boundaries included the raw material extraction, material processing, manufacturing, and assembly phases. Results indicated that the EGR had the least potential environmental impacts for the 15 impact categories considered. In addition, results showed that rebar, concrete, and thermal insulation were the main contributors to the environmental impacts for TGBR, while rebar, concrete, thermal insulation, and waterproof membrane were the highest contributors for WRR.

The second and third objectives were achieved by first installing one TGBR mockup and two EGR mockups on the rooftop of the Chemical Engineering Department at the University of Balamand in north Lebanon (34.36°N, 35.78°E). EGR mockups differed in the roof slope, the depth and the composition of their substrate. In particular, EGR8 had 0% roof slope and a substrate depth of 8 cm while EGR16 had 6% roof slope and a substrate depth of 16 cm. Each roof mockup was equipped with thermocouples, soil moisture sensors, and rain gauges to perform real-time temperature monitoring, real-time soil moisture monitoring, and water retention, respectively. In total, 12 thermocouples and 12 soil moisture sensors were installed between the different layers and at different depths of the substrate and measurements were taken every minute from mid-January until end-March 2016 (winter season). In addition, three rain gauges were connected to the water exhaust of each mockup while a fourth one was used to measure rainfall. Air temperature and relative humidity were also recorded at a height of 5 and 110 cm above the surface of the roof mockups. Temperature profiles at different substrate depths clearly indicated the reduction of the temperature fluctuations under the substrate layer, the heat storage effect, and the passive cooling effect even for sunny winter day ($T_{air\ max} = 32^{\circ}C$). These temperature profiles were used to calculate the heating/cooling demand of a residential house which, in turn, were used to determine the heating/cooling cost. Those costs together with the construction cost of 1m² of TGBR and EGR were utilized to perform a full economic study was. The economic study showed that EGR could save up to 45USD/200m²/month compared to TGBR. The water management performance of EGRs illustrated that the soil composition of EGR8 was more efficient than that of EGR16 from a water retention perspective. However, both EGR8 and EGR16 delay and reduce runoff water compared to TGBR. In contrast, EGR acted as a sink especially for cadmium, iron, calcium, and ammonium: cadmium load in runoff water was 0.01 mg/L for TGBR, 0.04 mg/L for EGR8,

and 0.025 mg/L for EGR16, while ammonium load was 0.525mg/L for TGBR, 1.2 0mg/L for EGR8, and 0.567 mg/L for EGR16.

This research demonstrated that VRs and in particular EGRs could offer a possible solution to the Lebanese energy deficit and water management issues. They can also reduce the potential environmental impacts of the roof during its lifetime.

RESUMÉ

Les toitures végétalisées (TTV), également appelées terrasses-jardin, sont des "systèmes qui favorisent la croissance des plantes sur les toits". Selon l'Association internationale des toits verts, les TTV existent en deux types : extensive et intensive. Ces deux types diffèrent principalement par le type de végétation, la profondeur du substrat et le poids particulièrement lorsque le substrat est saturé d'eau. Les toitures végétalisées extensives sont caractérisées par une faible épaisseur de substrat (< 200 mm) donc une gamme végétale restreinte, un poids relativement faible, un entretien limité et des coûts d'installation moyens. Par contre, les toitures végétalisées intensives sont marquées par un milieu de culture épais (> 200 mm) d'où la richesse de la gamme végétale, la lourdeur du système, l'importance de l'entretien, la nécessité d'utiliser de systèmes de support et les coûts d'installation élevés.

Sur le plan international, les TTV sont devenues de plus en plus populaires grâce à leur avantage environnemental, économique et énergétique. En particulier, les toitures végétalisées améliorent la qualité de l'air grâce à l'élimination des polluants par les plantes. D'un point de vue énergétique, l'installation des TTV peut être très efficace; d'une part, le substrat de culture réduit les fluctuations de température et d'autre part, les plantes rafraichissent l'air ambiant par transpiration et par photosynthèse tandis que l'action conjointe des deux, à savoir le substrat de culture et plantes est nettement bénéfique puisqu'elle atténue l'ampleur de l'îlot de chaleur urbaine sans parler de la valeur ajoutée en matière de bien-être environnemental et esthétique.

Au Liban, un pays du Moyen-Orient, seulement deux toitures végétalisées extensives ont été installées jusqu'à présent. En fait, l'installation de ces toitures au Liban s'avère être une option intéressante d'autant que le pays souffre d'une pénurie de plans contemporains nécessaires à son développement durable voire, d'une gestion radicale de son infrastructure; malheureusement, pareille infrastructure âgée et non rénovée depuis des décennies conduit souvent, à l'inondation des routes dans les zones urbaines durant la saison d'hiver, entre autres, à un déficit d'électricité et à un besoin continu d'utilisation de systèmes de chauffage/refroidissement.

Ces travaux de recherche visent à atteindre les objectifs suivants :

1. Déterminer et comparer les impacts environnementaux potentiels d'un toit de gravier ballasté traditionnel, d'une toiture réfléchissante, et des toitures végétalisées ;
2. Quantifier la performance énergétique et les besoins de chauffage et de climatisation d'un toit de gravier ballasté traditionnel et d'une toiture végétalisée extensive ;
3. Évaluer le potentiel de gestion d'eau et la dynamique de ruissellement d'un toit de gravier ballasté traditionnel et d'une toiture végétalisée extensive.

Le premier objectif a été atteint suite à une Analyse comparative de Cycle de Vie (ACV) d'une toiture végétalisée extensive de 834m², installée sur le toit de la Banque Centrale du Liban et de trois toits fictifs : toit de gravier ballasté traditionnel, d'une toiture blanche réfléchissante, et d'une toiture végétalisée intensive de même surface. L'ACV est un outil international utilisé pour évaluer les impacts environnementaux d'un produit, d'un procédé ou d'un service d'extraction des matières premières jusqu'à la fin de vie. L'unité fonctionnelle était : « La construction et installation d'un système de toiture pour couvrir une surface de 834m² pour 45 ans ». Les limites du système incluent notamment les phases d'extraction des matières premières, de traitement des matériaux, de fabrication et du montage. Les résultats indiquent qu'une toiture végétalisée extensive présente les impacts environnementaux les plus bas pour les 15 catégories d'impacts considérées. En outre, les résultats ont montré que l'acier, le béton et les panneaux d'isolation thermique sont les principaux contributeurs aux impacts environnementaux pour le toit de gravier ballasté traditionnel, tandis que l'acier, le béton, les panneaux d'isolation thermique et la membrane d'étanchéité sont les plus grands contributeurs pour les toitures blanches réfléchissantes.

Les aspects thermiques et hydriques des TTV (deuxième et troisième objectifs) ont été testés suite à l'installation d'une maquette de toit de gravier ballasté traditionnel et de deux maquettes de toitures végétalisées extensives sur le toit du département de génie chimique à l'Université de Balamand, au nord du Liban (34.36°N, 35.78°E). Les maquettes de toitures végétalisées extensives diffèrent par la pente ainsi que la profondeur et la composition du substrat. EGR8 est une maquette de toiture végétalisée extensive nivelée et d'un substrat de culture de 8 cm formé de sol, tourbe, alumine, pierre ponce et engrais alors que EGR16 est une maquette de toiture végétalisée extensive d'une pente de 6% et d'un substrat de culture de 16 cm formé de sol, tourbe, Pierre ponce et engrais. Chacune des maquettes a été équipée de thermocouples, de capteurs d'humidité du sol, et de pluviomètres afin de surveiller, en temps réel, la température, la teneur en eau, et la rétention d'eau. Au total, les 12 thermocouples et les 12 capteurs

d'humidité du sol installés entre les couches et à différentes profondeurs du substrat de culture, mesurent la température et la teneur en eau respectivement, chaque minute de mi-Janvier jusqu'à fin Mars 2016 (saison d'hiver). En outre, chacune des différentes maquettes a été équipée d'un pluviomètre afin de surveiller, en temps réel, l'eau de ruissellement et d'évaluer la quantité d'eau des précipitations. De plus, la température et l'humidité relative de l'air ont été enregistrées à 5 et à 110 cm au-dessus de la surface des maquettes. Les profils de température à différentes profondeurs du substrat indiquent clairement la réduction des fluctuations de température, l'effet de stockage de chaleur, et l'effet de refroidissement passif, même durant les journées ensoleillées d'hiver ($T_{air\ max} = 32^{\circ}C$). Ces profils de température ont été utilisés pour quantifier les besoins de chauffage et de climatisation d'un immeuble. À cet effet, la conversion de ces besoins en coût d'énergie en plus du coût d'installation d' $1\ m^2$ d'un toit traditionnel ou végétalisé a muni à une étude économique complète. L'étude économique a montré qu'une toiture végétalisée extensive pourrait économiser jusqu'à 45USD/200m²/mois par rapport à un toit de gravier ballasté traditionnel. D'autre part, les profils de la teneur en eau à différentes profondeurs du substrat ont démontré que la composition du sol d'EGR8 est plus efficace que celle d'EGR16. Toutefois, les deux EGR8 et EGR16 ralentissent et réduisent l'eau de ruissellement par rapport au toit de gravier ballasté traditionnel. En revanche, une toiture végétalisée extensive agit comme un système filtrant surtout pour le cadmium, le fer, le calcium et d'ammonium : la quantité de cadmium était de 0,01 mg/L dans l'eau de ruissellement du toit de gravier ballasté traditionnel, de 0,04 mg/L dans celui d'EGR8 et de 0,025 mg/L dans celui d'EGR16 tandis que la quantité d'ammonium était de 0.525 mg/L dans l'eau de ruissellement du toit de gravier ballasté traditionnel, de 1.20 mg/L dans celui d'EGR8 et de 0.567 mg/L dans celui d'EGR16.

Ces travaux de recherche ont démontré que les toitures végétalisées, en particulier les toitures végétalisées extensive, pourraient offrir une solution possible aux problèmes de déficit énergétique et de gestion d'eau dans le contexte Libanais. Ils peuvent également réduire les impacts environnementaux potentiels d'un toit pendant sa durée de vie.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACV	Analyse de Cycle de Vie
CDD	Cooling Degree Day
CEDRO	Country Efficiency and Renewable Energy Demonstration for the recovery of Lebanon
DB	Decibel
DD	Degree Day
EDL	Electricity du Liban
EEA	European Environmental Agency
EGR16	Extensive Green Roof with a substrate depth of 16 cm
EGR8	Extensive Green Roof with a substrate depth of 8 cm
EGRs	Extensive Green Roofs
FU	Functional Unit
G&SD	Goal and Scope Definition
HDD	Heating Degree Day
IGRs	Intensive Green Roofs
IMPACT	Impact Assessment of Chemical Toxics
In	Inch
IR Radiations	Infrared Radiations
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

L-LCA	Lebanese-Life Cycle Assessment
RH	Relative Humidity
TGBRs	Traditional Gravel Ballasted Roofs
UHI	Urban Heat Island
UNDP	United Nations Development Program
UV-RAYS	Ultraviolet rays
VRR	White Reflective Roofs
VRs	Vegetative Roofs

PREFACE

This doctoral work lead to several manuscripts as well as many communications presented in the context of various international conferences. All these manuscripts and scientific communications are summarized in the following table.

Table 1: Manuscripts and communications generated during this doctoral thesis

Type	Details	Date
Manuscript	El Bachawati, M., Manneh, R., Belarbi, R., El-Zakhem, H. Performance of extensive green roofs towards rainwater runoff quantity and quality: A Lebanese case study. Submitted to Ecological Engineering .	2016
Manuscript	El Bachawati, M., Manneh, R., Belarbi, R., & El Zakhem, H. (2016). Real-time temperature monitoring for traditional gravel ballasted and extensive green roofs: A Lebanese case study. Energy and Buildings , 133, 197-205.	2016
Manuscript	El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., & El Zakhem, H. (2016). Cradle-to-gate life cycle assessment of traditional gravel ballasted, white reflective, and vegetative roofs: A Lebanese case study. Journal of Cleaner Production , 137, 833-842.	2015
Conference	El Bachawati, M., Manneh, R., Belarbi, R., El-Zakhem, H. Real-time temperature monitoring for an Extensive Green Roof and a Traditional Gravel Ballasted Roof: A Lebanese case study. Twenty second Lebanese Association for Advancement of Science international conference (LAAS 22), 14-15 April, 2016, Beirut, LEBANON .	2016

Table 1: Manuscripts and communications generated during this doctoral thesis (continued)

Type	Details	Date
Conference	El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., El-Zakhem, H. Life cycle assessment of extensive, intensive and traditional gravel ballasted roofs. First International Conference on Bio-based Building Materials (ICBBM), 21-24 June 2015, Clermont-Ferrand, FRANCE .	2015
Conference	El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., El-Zakhem, H. Life Cycle Assessment of vegetative, reflective and traditional roofs: A case study for the Lebanese context. Twenty fifth Society of Environmental Toxicology and Chemistry conference (SETAC Europe 25 th), 3-7 May 2015, Barcelona, SPAIN .	2015
Conference	El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., El-Zakhem, H. Comparative Life Cycle Assessment of vegetative and traditional gravel asphalted roofs: A Lebanese case study. Twenty first Lebanese Association for Advancement of Science international conference (LAAS 21), 15-17 April, 2015, Beirut, LEBANON .	2015

INTRODUCTION

Sustainable development is defined as “the development that meets the human need to feel well-being without compromising with the natural resources and ecosystems on which future generations depend” [1]. Sustainable development relies mainly on environmental, social, and economic dimensions. Reaching sustainable development remains a serious challenge. The deterioration of air, water and soil quality, climate change, increase of non-renewable energy consumption, and unemployment levels are all indications of an unsustainable development. One way to achieve sustainability is to reduce unused and impermeable surfaces by installing more Vegetative Roofs (VRs) especially on industrial and commercial buildings.

In line with that, VRs are an important technology and planning tool that can be used to mitigate problems associated with storm water runoff, Urban Heat Island (UHI) effect, wildlife habitat, as well as air and runoff water quality [2, 3]. These roofing systems could complement and/or replace Traditional Gravel Ballasted Roofs (TGBRs). Moreover, the idea of using soil and vegetation to protect the outer building materials is not a new concept but rather goes back as far as biblical times and the Tower of Babylon [4]. In recent times, Germany is taking the lead of research studies and market growth for VRs compared to other European countries. For instance, VRs cover 13 million square meters (equivalent to one-sixth of new roofs) in Germany and one million square meters (equivalent to one-thirtieth of total area) in France. Austria, Switzerland and Norway have also implemented policies and incentives to develop VRs in urban areas [5].

Compared to Europe, Lebanon, a Mediterranean country, lacks a clear sustainability plan as well as an infrastructure update and management leading to road flooding in urban area amongst other things such as the case of water and electricity sectors. Although the installation of VRs could be an interesting option for Lebanon, there are several barriers to the widespread adoption of this technology. So far, only two VRs have been installed.

This research focuses on:

- 1) Potential environmental impacts of TGBRs, White Reflective Roofs (WRRs), and VRs;

- 2) Thermal profile and the heating/cooling demand, during a Lebanese winter season, of both TGBRs and Extensive Green Roofs (EGRs) ;
- 3) Water management and runoff water quality of both TGBRs and EGRs during a Lebanese winter season.

The first objective was reached through a Life Cycle Assessment (LCA) study, the second one through a real-time temperature monitoring at different substrate depths along with heating/cooling degree days' calculations, and the last one through a real-time soil moisture monitoring at different substrate depths with runoff water quality tests.

In this respect, the first chapter of the manuscript elaborates the literature review which helped to state research hypothesis. The second chapter focuses on the research hypotheses, the objectives, and the general methodology. Chapters three, four and five expounds the three scientific papers under review or accepted in international journals. Lastly, a general discussion of the results of the three publications is presented in chapter six, followed by contributions and recommendations.

CHAPTER 1 LITERATURE REVIEW

This chapter denotes a synthesis of the bibliographical work on TGBRs, WRRs, and VRs. It is structured in four parts:

- First part is devoted to definition, components, advantages, and disadvantages of TGBRs,
- Second part is dedicated to description, constituents, benefits, and drawbacks of WRRs,
- Third part explores the explanation, ingredients, advantages, and limitations of VRs,
- Fourth part deals with history, phases, and types of LCA, in addition to the particular case of Lebanon.

1.1 Different types of roofs

The type of roofs varies based on the structure and the composition. They could be classified as TGBRs or black roofs, WRRs or cool roofs, and VRs or green roofs.

1.1.1 Traditional Gravel Ballasted Roofs (TGBRs)

TGBRs were initiated in the early 1970s. TGBRs are basically formed from a solid slab of concrete, rebar or wood covering the top of a building [6]. The solid slab is protected by a gravel layer against the direct UV exposure and to better withstand mechanical damage caused by rain, snow, wind, and sunlight [7]. Overall, TGBRs could be utilized for either flat or low sloped roofs.

1.1.1.1 Components of traditional gravel ballasted roofs

As shown in **Figure 1-1**, TGBRs consist, from the bottom to the top, of roof assembly, waterproof membrane, filter sheet, and gravel or crushed stone layer (pebbles) [7].

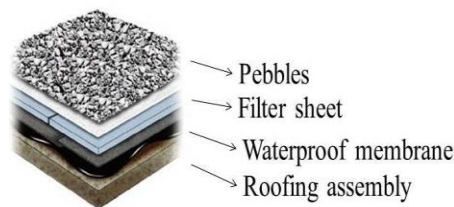


Figure 1-1: Components of TGBR

1.1.1.1.1 Roofing assembly

Roof assembly, displayed in **Figures 1-2.a & 1-2.b**, is a mixture of hollow concrete blocks, rebar and concrete [8, 9]. The simplest form of concrete is a mix of paste and aggregates. Paste is made of cement and water in a specific proportion depending on the climate conditions while aggregates could be sand, powder line stone, crushed gravel, or gravel. Due to the hydration reaction, the paste hardens and form a rock-like mass known as concrete [10]. One other component of the roof assembly is the Hollow concrete blocks constituted of paste, aggregates and compressed in a specific mold.

1.1.1.1.2 Waterproof membrane

Mastic asphalt, illustrated in **Figure 1-2.c**, is one of the most traditional building materials in the world for it is a waterproof cover compatible with flat, sloped or curved roofs. This liquid waterproofing layer endorses numerous advantages such as durability, recyclability, incombustibility, and fast installation [11, 12]. Furthermore, this dark black liquid could be laid on concrete, timber and metal decking by dispersing it by hand with a float rather than a roller [11, 13].

1.1.1.1.3 Thermal insulation layer

Thermal insulation boards, presented in **Figure 1-2.d**, are made of extruded polystyrene and mostly installed between waterproof membrane and filter sheet for TGBRs and between waterproof membrane and root resistant barrier for VRs. These boards contain in average 20% of pre-consumer recycled content, and are easily installed, maintained, and resistant to moisture infiltration and condensation. Besides, the extruded polystyrene boards reduce heat loss or gain, which is required to improve the comfort level and increase the building lifetime [14].

1.1.1.1.4 Filter sheet

Filter sheets, exposed in **Figure 1-2.e**, are thin and light filter layers made of polymeric fibers or polyolefin and are easily installed. These filters are resistant to mechanical stress, chemically and biologically neutral, but are neither waterproof nor anti root [15, 16].

1.1.1.1.5 Pebbles

TGBRs are “free standing”; contractor simply spread the filter sheets without fastening them to the roof assembly. So the pebbles layer placed on top has double role: the first to overload below layers to be fixed to the seats and the second to filter rain water from big particles before

reaching the drainage. In case of TGBRs, stones or crushed stone (**Figure 1-2.f**) are at least an inch in diameter [17].



Figure 1-2: TGBR components: (a & b) roof assembly (c) mastic asphalt (d) thermal insulation boards (e) filter sheet (f) pebbles

1.1.1.2 Advantages of traditional gravel ballasted roofs

TGBRs are well known for the fast installation and low cost. In some cases, pebbles layer is substituted by pavers which are easier to walk on and more colorful. TGBRs are prevalent because of some benefits [6, 8, 17, 18]:

- Rapidly installed,
- Provide quick watertight structure,
- Fully recyclable at the end of their life cycle,
- Weak chance to damage the mechanical and electrical infrastructures close to the roof assembly,
- Installed in a wide range of temperature and weather conditions,
- Easily repaired since the added layers are effortlessly taken up.

1.1.1.3 Disadvantages of traditional gravel ballasted roofs

Due to the additional layers, in particular the pebbles layer, TGBRs present many disadvantages such as:

- The gravel layer adds a lot of weight to the roof system, typically 240 to 600 kilograms per square meter [6],
- The main difficulty is to find and patch a leak in TGBR, since the roof assembly is well hidden,
- Over time, ballast stone fractures which can hole the filter sheet,
- In windy areas, TGBRs are not recommended because stones could fall down from the roof and hit the people or the objects below.

1.1.2 White Reflective Roofs (WRRs)

WRRs are marked by high reflectivity and emissivity [19]. WRRs are designed in a way to reflect more sunlight and absorb less heat compared to TGBRs [20]. A roof with both high reflectivity and high emissivity is suitable to save cooling energy during the summer season. In fact, high emissivity is also significant for decreasing the UHI effect [21].

1.1.2.1 Components of white reflective roofs

Components of WRRs, showed in **Figure 1-3**, are mechanically fixed and are listed, from the bottom to the up, as: roof assembly, waterproof membrane, thermal insulation layer, and white reflective membrane.

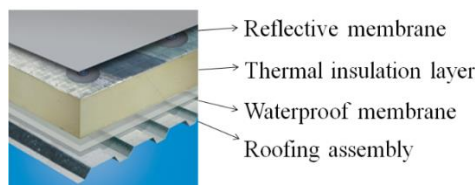


Figure 1-3: Components of WRRs

1.1.2.1.1 Waterproof membrane

Reinforced concrete roofs have pores or capillary tracts interconnected within the concrete. Thus, cracks and voids could appear due to thermal expansion, contraction, and shrinkage. As a result, water will be able to penetrate through these capillary tracts and voids, especially due to osmosis. Correspondingly, membrane roofing is directly installed above the roof assembly to prevent leaks and move water off the roof [22, 17, 23]. Commonly, there are three types of roof membrane: the first is made of synthetic rubber, the second of thermoplastic, and the third is a modified bitumen membrane [24]. The latter (**Figure 1-4.a**) is the one used in this study to keep the roof impervious and it is also referred to as APP, SBS, and SEBS [25].

1.1.2.1.2 Rockwool blanket

Mineral rock wool blanket (**Figure 1-4.b**) is a lightweight and flexible rolling product that could be covered with stainless steel wire mesh or with iron wire mesh. It is made from slag and basalt rock, thus it is a non-combustible product and highly resistant to fire. In addition, it is characterized by high thermal insulation and waterproofing properties.

1.1.2.1.3 Reflective membrane

A white reflective membrane is the outer layer of a WRR, and is made of Polyester. The advantages of such membrane are resistance to UV rays, easiness of installation, and high reflectance which enhance the lifespan of the layers below. Also, this membrane with a modified bitumen membrane could be welded using a propane torch with an overlap of 10cm (**Figure 1-4.c**). The propane torch heats and melts the seams together in order to create a seal. [26, 27].

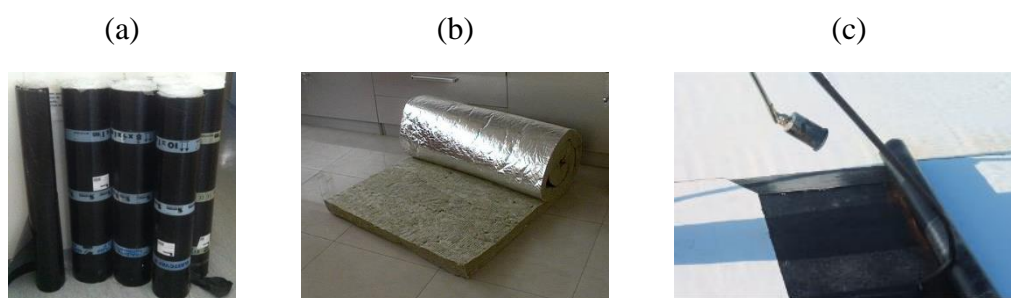


Figure 1-4: (a) Waterproof membrane (b) rock wool blanket, and (c) reflective membrane [26].

1.1.2.2 Benefits of white reflective roofs

WRRs positively influence the building or the home owner in addition to the surrounding especially when installed on many buildings. Some of the immediate and long-term benefits are:

- Lowering the annual electricity bills by decreasing the heating/cooling consumption [28],
- Mitigating UHI effect in the city and its suburbs by reflecting solar radiation instead of absorbing or transferring it into the building [29],
- Lowering heat in a non-air-conditioned workspace which will improve work conditions and employees' productivity,

- Protecting underlying layers from deterioration by reflecting ultraviolet rays (UV-rays) and infrared (IR) radiations; thus, extending roof lifetime and reducing roof maintenance [30].

1.1.2.3 Drawbacks of white reflective roofs

Some of the drawbacks of WRRs are the following:

- In 2011, at the University of Stanford, Scientifics suggested that WRRs increase the global temperature despite the reduction of temperature in the interior of a single house and the reduction of the UHI effect [31],
- In cold seasons, homes with snow on their rooftops need more heat since snow will cover them for a longer period,
- In 2012, at the University of California, researchers demonstrated that a WRR rises the temperature in the surrounding buildings. This is due to the reflected solar radiation knowing that these buildings are fitted with reflective glass. As a result, the need for cooling systems will increase, leading to an increase in the energy use [32, 33],
- Over time, the white reflective surfaces get dirty and lose some characteristics of reflection and emittance.

1.1.3 Vegetative Roofs (VRs)

VRs are defined as specialized coverage systems that foster the growth of plants on rooftops [34, 35]. VRs could retrofit industrial, commercial, and private buildings residences. Nowadays, some legislations are made to impose VRs on all new commercial buildings such is the case in Paris [36].

In the text below, the term "vegetative roof(s)" will be used rather than "green roof(s)" because a non-vegetative roof could be considered as environmentally "green" roof without being a vegetative roof. For example, WRRs mitigate heat gain within a building [32]; therefore, might be labeled as "green" or environmentally friendly without being vegetative roofs.

1.1.3.1 Components of vegetative roofs

VR is a layered system comprising, from the bottom to the top, the following layers: roof assembly, waterproof membrane, root resistant barrier, thermal insulation boards, drainage layer, filter sheet, growing medium and vegetation [37, 38] as illustrated in **Figure 1-5**.

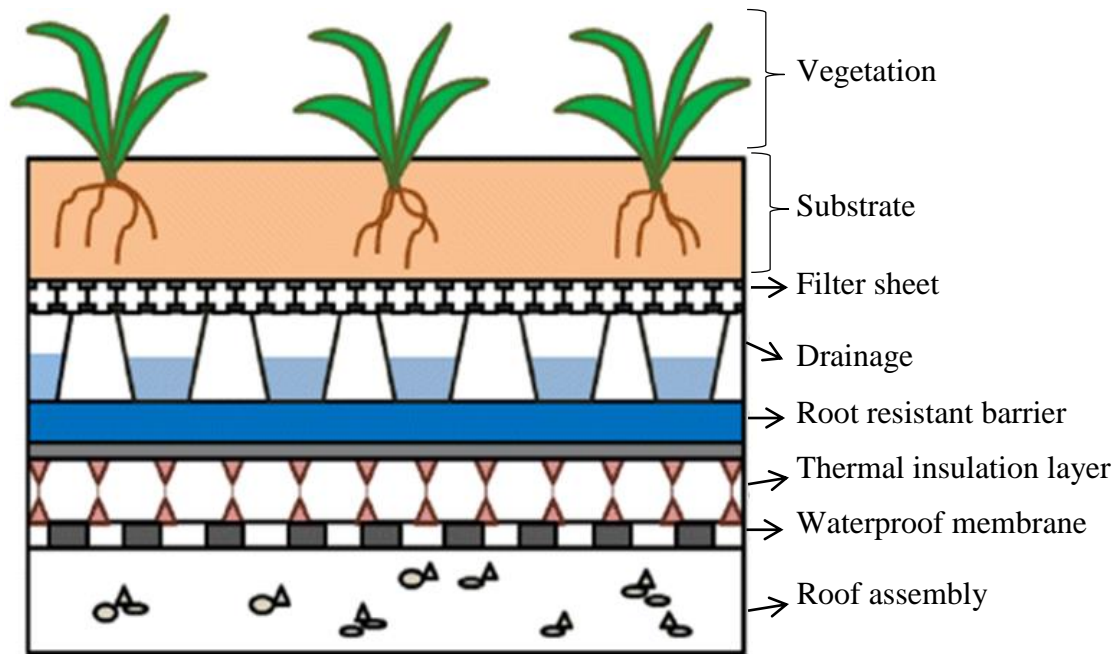


Figure 1-5: Cross-section view of VRs [39]

1.1.3.1.1 Root resistant barrier

The root barrier (**Figure 1-6.a**) is made of high-pressure polyethylene and is usually installed on top of the thermal isolation membrane. This membrane provides the protection to the underlying waterproofing membrane from root penetration and microorganisms in the substrate [40]. The growth and movement of roots through substrate fetching water and nutrients could, over time and without accurate protection, crack the roofing assembly where water can seep. Thus, the root resistant membrane contributes in increasing the lifetime of the roofing assembly [41].

1.1.3.1.2 Drainage layer

The drainage and water storage element is made of recycled polyethylene and are sometimes designed for pathways to withstand high mechanical pressure. Respectively, this layer contains multi-flow channels system, openings for ventilation and evaporation, in addition to cavities retaining water for vegetation in dryer periods. In this respect, it is installed directly below the growing medium [22, 42].

Furthermore, the drainage element (**Figure 1-6.b**) stores water even on sloped roofs, is biologically resistant and easily installed [42]. An effective drainage layer must reduce the risk of water leaks, evacuate additional water volume, and maintain roofs structural capacity. At the same time, it protects the root resistant barrier from excess water which promotes plant roots to grow and consequently pierce the root resistant barrier [43].

1.1.3.1.3 Filter sheet

A filter sheet (**Figure 1-2.e**) separate drainage layer from growing medium. In fact, filter sheets allow the water diffusion until the drainage layer, provide moist environment for plant roots, and keep the fine particles constituting growth medium out of the drainage layer [44]. As it is the case for the drainage layer, filter sheets are chemically and biologically resistant and should be installed with an overlap of at least 10 cm [16, 40].

1.1.3.1.4 Growing medium

The growing medium, the heaviest element of a VR, is a natural and living layer implemented over different functional layers. This layer is an essential component of VR making the presence of other layers valuable, and its composition is very particular since the environment on the roof is different than that on the ground for traditional plants. Furthermore, the decrease in moisture and drought, the variation of temperature, the high level of wind, and the solar radiation create hostile locations for plants growth [45]. In line with that, growth medium must retain nutrients and water for plants to survive, and must be lightweight and well drained to alleviate the roof structural load. More to the point, a typical substrate is a mixture of recycled materials, minerals, compost, aggregates, and light absorbent stone bark (Pozzolan, Expensed Clay ...) [46, 47]. Based on the literature, there are no standard compositions or technical opinions about proportions and nature of the individual components of a growing media. The most common composition is: 50 – 80 % by vol. aggregates, 0 – 10 % by vol. compost, and \leq 50% by vol. sand or soil [48]. **Figures 1-6.c, 1-6.d, and 1-6.e** highlight soil, pumice and, compost, respectively.

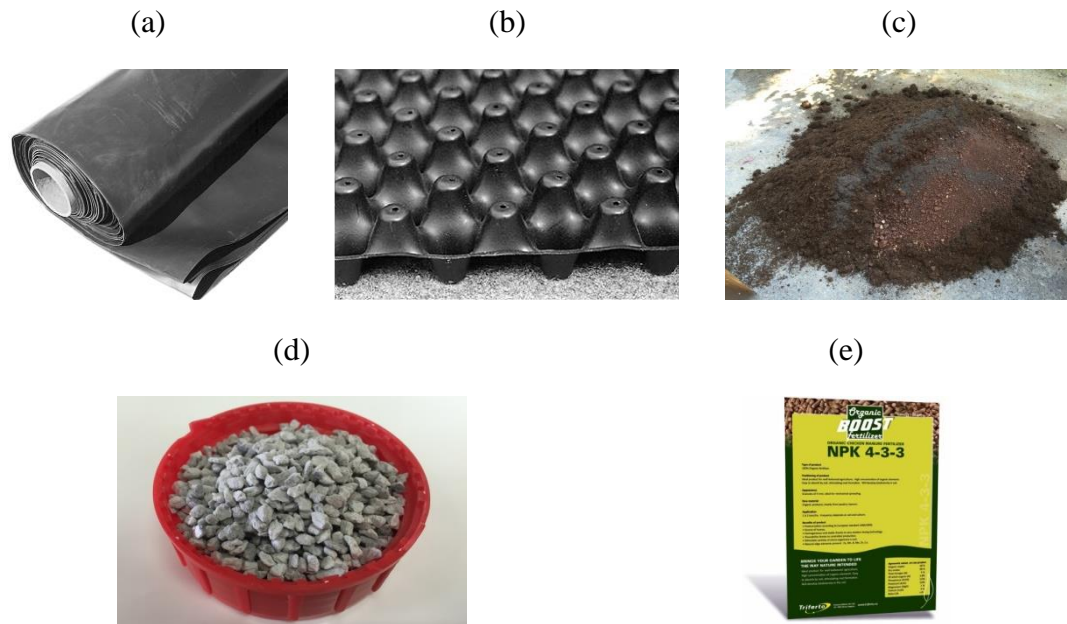


Figure 1-6: (a): Root barrier, (b): drainage board, (c): soil, (d): pumice, and (e) organic fertilizer [42, 49]

Substrate hosts plants and provides the nutrients and water needed for the biological functions (growth and life) [50]. The depth of the substrate depends on the type of vegetation; for example, small vegetation (e.g.: sedum) requires less depth for the roots compared to what a shrub may require [51].

1.1.3.1.5 Vegetation

In general, vegetation is chosen based on type of VR and on local climate. The vegetation layer is the artistic layer of a VR. However, pursuant to agriculturalists expertise, there are three types of greenery: cuttings, plug plants, and pre-cultivated elements.

The focus is generally made on plants that are highly resistant to extreme temperatures and quickly set up to cover the soil surfaces to reduce its drying by sun and wind. Ground cover plants have also the advantages of leaving little room for wild or weeds and diminishing maintenance.

1.1.3.1.5.1 Cuttings

Figures 1-7.a displays cuttings, the most profitable and handy mode of planting with a growing period of 3 to 4 seasons. To be planted, cuttings are spread into the substrate ($60\text{--}80\text{ g/m}^2$) and covered with a thin layer of organic mulch [52].

1.1.3.1.5.2 Plug plants

The plug plants is the most common method of planting. **Figures 1-7.b** reveals a small single plug plant directly installed in the growing medium (16-20 plugs/m²). The establishment period is between 1 and 2 growing seasons.

1.1.3.1.5.3 Pre-cultivated vegetation blanket

This type of greenery provides an immediate planting coverage right after installation. The pre-cultivated vegetation blankets (**Figures 1-7.c**) are pre-grown on a biodegradable base layer and delivered to the roof in rolls. The establishment period will take no more than 1 growing season [53].

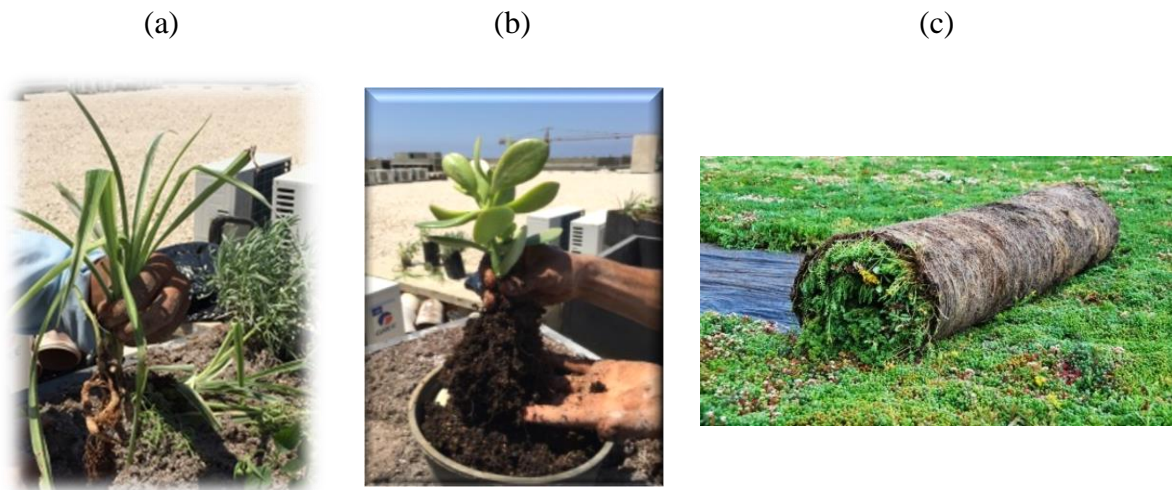


Figure 1-7: (a) Cutting, (b) plug plants, and (c) blanket [54]

1.1.3.2 Types of vegetative roofs

VRs are typically divided into two main categories: Extensive Green Roofs (EGRs) and Intensive Green Roofs (IGRs) represented in **Figures 1-8.a and 1-8.b** respectively [55].

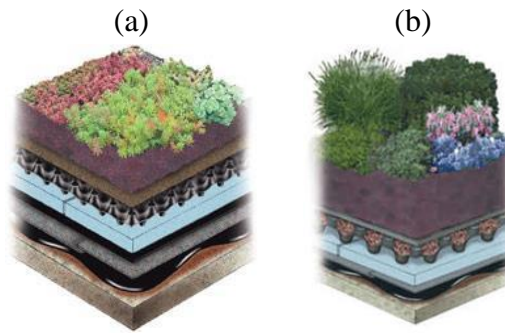


Figure 1-8: (a) EGR (b) IGR

The choice of a VR depends on different elements, such as the expected use of the rooftop, the strength of supporting structure, the thickness of stratigraphy, the type of vegetation, and the costs required for maintenance [56, 57]. **Table 1-1** summarizes the differences between EGRs and IGRs.

Table 1-1: Differences between EGRs and IGRs [45, 55, 57, 58,, 59, 60]

	EVRs	IVRs
Growing medium depth	< 200 mm	> 200 mm
Vegetation	Sedums, succulent, and grasses	Grasses, perennial herbs, shrubs, and large trees
Weight	50 – 150 kg/m ²	300-500 kg/m ²
Maintenance	Low maintenance	High maintenance
Cost	88.0 USD per m ²	165.0 USD per m ²
Irrigation	No	Regularly
Accessibility	For maintenance only	Open for public

1.1.3.2.1 Extensive Green Roofs (EGRs)

EGRs are the simplest and the lightest type of VRs [57, 61]. This greening roof (**Figure 1-9.a**) is established with thin soil layers (< 200 mm). Because of the shallower depth, it only sustains small plants such as grasses, succulents, herbs, mosses, and drought tolerant such as sedum [62, 63]. Commonly, these plants are known for high climate change resistance, leaves water storage, and shallow root development. Therefore, these plants are ideal for thin substrates with maintenance free. A mixture of these plants creates a pleasant vegetal community [55].

Besides the lightweight and the esthetic view of EGRs, irrigation or any specialized drainage system are not required; this makes it suitable for residential homes and commercial buildings without any additional strengthening [34, 38, 61].

1.1.3.2.2 Intensive Green Roofs (IGRs)

An implementation thicker than EGR is referred to IGR (**Figure 1-9.b**). The latter is established with a soil thickness > 200 mm, and could support larger plants such as trees, shrubs, and hardscapes similar to landscaping found at ground level [55, 62, 63]. Typically, because of the diversity of plants used, IGR requires significant maintenance efforts in the form of weeding, fertilizing, and watering [55, 57, 61].

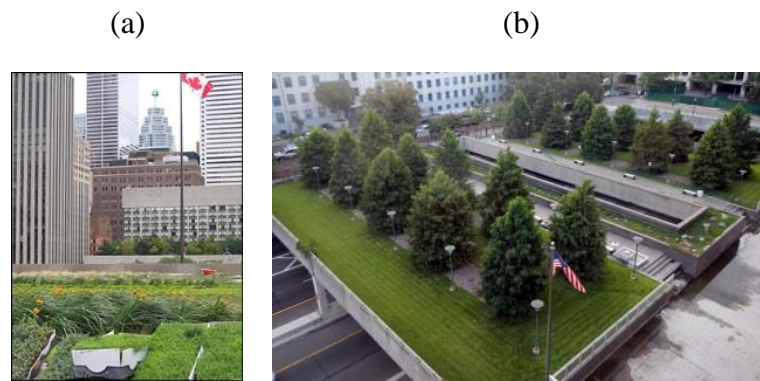


Figure 1-9: : (a) City Hall Podium, Canada and (b) Tax Court, U.S.A

IGRs, also tend to be more expensive than EGRs (165.0 USD/m² compared to 88.0 USD /m²) because of the need for a more structurally sound building to support the weight [62]. Due to the shallower depth and to the vegetation diversity, IGRs are frequently designed as public places. However, several elements restrict the design of IGRs but to newly constructed buildings because of highly resistant anti roots barrier, structure support, constant maintenance, high loading, intensive irrigation, complex drainage systems, and high cost [34, 62].

1.1.3.3 Benefits of vegetative roofs

More and more the human population is increasing together with the need for more impermeable surfaces in cities and towns such as buildings, roads, and parking lots [64]. This in return has numerous negative consequences on cities infrastructures and surrounding environment. While VRs could present a solution for this serious problem, their qualifications still underestimated although the modern green roof technology dates back to the 1960s in Germany [65].

The "esthetic view" is the only obvious advantage within the wide range of pros for VRs. Further environmental benefits of VRs include stormwater management [57, 61, 66], improving runoff water quality [67], reducing noise and urban air pollution [69-71], increasing vegetal and animal biodiversity in cities [63, 73, 74], extending roof lifetime [57, 70-78], mitigating UHI effect [3, 76, 79-81], and saving energy [57, 70-78, 82]. These and other benefits are detailed in the text below.

1.1.3.3.1 Aesthetic improvement

For long, urban greening was promoted as an easy and effective strategy for building embellishment and rising investments. From this perspective, a layer of plants enhances good designs or disguises bad ones [83]; plants could add visual interest to the roofs, soften industrial and commercial properties [84], and allow a new building to blend in a rural surrounding. Such is the case of the new public library in Vancouver-Canada which was designed with a VR specifically to offer a better view to the residents of the surrounding office towers [85].

1.1.3.3.2 Stormwater management

VRs are considered a viable approach to improve urban storm water management [61]. During drought periods, the rain water stored in the substrate is utilized by plants, transpired to the atmosphere, or evaporated. In fact, retained water volume depends on many factors, such as type of VR, composition and depth of the growing medium [86], slope of the roof [87], plant species, moisture of the substrate, time interval between two rain events, in addition to intensity and duration of the rainfall [62, 88]. Despite all these factors, in general, summer retention rate is from 70 to 90% of precipitations compared to a range between 25 and 40% in winter [89]. For example, Deutsch *et al.* state that if VRs reached 20% of the impermeable surface areas, 958×10^6 liters per year (253×10^6 gallons per year) of rainwater could be stored in Washington, DC [90].

Moreover, VRs reduce runoff water volume, moderate water temperature, delay runoff peak time, and act as natural filters of the runoff water [41, 91]. Many heavy metal and nutrients carried by the rain end up being bound in the substrate instead of being discharged in runoff water. For instance, a Belgian manufacturer has a biodegradable factory with $8,000\text{m}^2$ of native grasses and wildflowers on its roof. The produced effluents are treated and filtered through the VR and reused as irrigation and nutrient source for plants [85].

1.1.3.3.3 Sound Insulation

Planted areas are assumed as natural soundproof areas due to substrate, vegetation layer, and air trapped between plants and roofing assembly [91]. This is a very useful way to isolate buildings near airports, noisy nightclubs, and factories. Usually, growing medium blocks low frequencies, while high frequencies are blocked by plants. Experiments demonstrated that a VR with a substrate of 5 in. thickness reduces the sound by 40dB, while a VR with a substrate of 8 in. thickness reduces the sound by 46dB [92, 93].

1.1.3.3.4 Improvement of Air quality

In urban areas, air pollution is due to the vertical thermal air movements. These movements are created when concrete, stone, glass, asphalt surfaces of roads, parking lots, and buildings are heated during summer season. At this moment, dust and dirt particles found on the ground and in the air, are carried out and spread [94, 95]. Plants subsequently improve air quality by filtering airborne particulates and gaseous contaminants [60, 89]. More to the point, airborne particulates stuck in leaves, branches and stem of the plants whereas gaseous pollutants are absorbed through photosynthesis and then trapped in leaves [92]. By moderating indoor temperature through VRs, the working hours of power plants is decreased, leading to a considerable decline in the amount released in the air of CO₂ and of other polluting by-products [96]. This offers an indirect air quality benefit of installing VRs on large surfaces.

Upon technician expertise, direct removal rates of air pollutants are not estimated to be high for VRs. Hence, when accumulating these removal rates with the reduction of the UHI effect, smog and electrical demands are declined. It is therefore evident that VRs could play a role in improving urban air quality.

1.1.3.3.5 Building envelope protection and life extension

VRs shield the roof assembly layer from UV-rays, IR radiations, heat stress, temperature fluctuations, and physical damage caused by maintenance, all of which lead to several defects in the roofing materials [84]. Hence, VRs would ensure less expansion and contraction stress on the base roof membrane by reducing membrane cracking and increasing the roof lifespan [84]. In fact, a long lifespan minimizes the need for re-roofing, consequently, maintenance costs and the amount of landfill waste are effectively decreased [95]. For instance, a London department store installed a roof membrane under a VR in 1938, 50 years later the membrane

was still in excellent condition although the average life span of flattest roofs in London is between 10-15 years [83].

1.1.3.3.6 Mitigation of urban heat island effect

UHI is defined as “a city or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities” [97]. There are two main sources of UHI effect, one the land surfaces modification where vegetative surfaces are substituted by impervious ones, and two the heat generated by industry, vehicles, and mechanical equipment [95, 98, 99]. VRs and WRRs play an important role in mitigating UHI effect by covering the hottest rooftops especially in urban areas and by decreasing the indoor temperature [97].

Besides, VRs decrease heating demand in cold days, cooling demand in warm days, and reflected heat in the surrounding neighborhood, as well as influencing air humidity and quality. In a summer day, TGBR temperature rises up to 60°C while grass roof temperature would not rise above 25°C [10]. This is due to the plants evapotranspiration by giving off water vapor to help cool the building, similarly to the effect of cooling human bodies by sweating.

During 22 months of observation, Liu and Baskaran from the national research council in Canada stated that the temperature of TGBR base membrane was greater than 30°C for 342 days, 50°C for 219 days, and 60°C for 89 days. In parallel, the temperature of VR base membrane exceeded 30°C for 18 days and never reached 40°C. As a result, the VR base membrane temperature fluctuation had a median of 5–7°C compared to 42–47°C for TGBR base membrane implying an obvious mitigation of the roof temperature [35].

1.1.3.3.7 Building Insulation

One of the key drivers to VRs is reducing the energy consumption of a building all year round. Or, the aim of insulation is to minimize the rate of heat transfer between the inner and the outer of a building. During hot months, VRs reduce the amount of solar radiation captured by the roofing assembly. On the contrary, during cold months, the internal heat is barred from escaping, and is reflected or absorbed [58, 82, 100].

Peck *et al.* found that VRs reduce the inner temperature 3 to 4°C when outdoor temperature ranges from 25°C to 30°C [101]. Indeed, lowering the indoor air temperature by 0.5°C will reduce the electricity consumed through cooling systems by up to 8% [102]. In general, buildings consume 65% of the total electricity consumption, therefore installing VRs on wide scales will highly affect the energy saving [103]. For instance, if all buildings in Chicago are

covered by VRs, the annual saving could reach up to one billion USD [104]. Correspondingly, in moderate and hot countries, VRs are more effective for the insulation of the growing medium is more efficient when air space exists in pores, whereas in cold countries pores are mostly saturated by the rainfall water [41].

1.1.3.3.8 Preservation of habitat and biodiversity

With ongoing sub-urbanization, buildings, malls, etc. VRs might be the hometown of many types of microorganisms and insects including spiders, beetles, flies, leafhoppers, ants, bees, and bugs [105-107]. Because EGRs are not publicly accessible, the soil becomes a safer habitat for insects and bird species that only nest on the ground [76].

Such is the case in one of the worlds' largest VRs in Dearborn-U.S.A., on top of Ford motor company assembly plant, where the 42,900 m² VR consists of a mix of 13 sedum species planted in less than 7.6 cm media. Within 2 years of initial plant establishment, 29 insect species and two bird species were identified [105].

1.1.3.3.9 Tax reduction

For economic and financial reasons, sewer and stormwater systems are not separated in many American cities and European towns; thus, charging the homestead and buildings' developer additional taxes on the basis of discharged amount per site. For example, Illinois State in USA passed in 1996 a law that endorses the planting of vegetative zones in general and VRs in particular. The aim of this law is to reduce property taxes since a VR reduces the storm water runoff [62, 101].

1.1.3.3.10 Fire delaying

In Stuttgart, the leading VRs city in Germany, researchers are investigating whether or not VRs provide enough fuel to sustain or propagate fires. During dry season, it was expected that fires on VRs will ignite the organic material present in the growing medium and dry plants will spread the fire across the roof. However, this was not the case. Instead, it was approximately impossible to set a healthy EGR on fire. That is probably why insurance companies offer a 10–20% discount on fire insurance when an EGR is installed.

1.1.3.3.11 Health benefits

Several studies ensure that there is a link between physical/mental health and natural view. One of these studies was done by Dr. Roger S. Ulrich in 1984. He concluded that natural view

lowered job stress, headaches, and sick leaves taken by employees, and raised job satisfaction and productivity. Dr. Ulrich also compared patients after a certain surgery with a natural view and those without. Patients with a natural view made quicker recoveries with fewer negative evaluations from nurses and lower rates of medication [108]. This might be due to the additional oxygen, air filtration and humidity control supplied by the plants.

1.1.3.3.12 Job creation

Although no exact figures exist, it is demonstrated in Europe that potential jobs creation correlated to VR technologies is very promising. The annual growth of roofing industry in Germany is between 15 and 20% since 1982. If all low slope roofs were to be greened, this figure would increase to approximately 100,000 full-time jobs [109]. The installation of VRs creates and enhances lot of job markets including suppliers and manufacturers of different roof's layers, designers, roof consultants, contractors, and companies supplying maintenance contracts.

1.1.3.4 Limitations of vegetative roofs

The installation of a VR is not a last minute job especially when talking about an IGR. The owner of a house or residence should communicate with the construction engineers and architects at the design phase about the expected usage of the VR. When designing a VR, many aspects should be taken into consideration including: increased capital costs, structural limitation, water leaks and waterproofing problems, lack of technical information, in addition to maintenance cost and care.

1.1.3.4.1 Increased capital costs

VRs have higher capital cost than TGBRs and WRRs. The capital cost of TGBR is usually 50 to 100% less than EGR and at most 100% less than IGR. However, this capital cost does not include neither the cost of the reinforcing structural support nor the long term savings. [11].

1.1.3.4.2 Structural limitation

The weight of EGR and IGR are 50-150 kg/m² and 300-500 kg/m² respectively. The load increase should be taken into account and supported by the structure of the building. That's why EGRs retrofit almost all the existent flat roofs without the need for reinforcing structural support. However, the depth of growing media and foot traffic in the case of IGRs impose the

necessity of additional reinforcing structural support, especially when saturated with rainfall water or snow melting [77, 110].

1.1.3.4.3 Water leaks and waterproofing problems

Even if most of VRs include root barriers, the plants' roots could reach the waterproof membrane, producing a damage to the structure of the building. This problem could be avoided or prevented by a yearly inspection, or by using a thin substrate so the plants could not grow enough to develop robust and deep roots. But in all cases, due to the complexity of VR system, localizing the leak and repairing it is a very challenging and costly process. Leak detectors could be used as a solution for this problem but could however increase the capital cost of VRs.

1.1.3.4.4 Lack of technical information

Currently, VRs are not very common and widespread in Lebanon, thus the know-how of the Lebanese contractors and the maintenance personnel is in its early stages. That is why, importing specialist contractors is an additional reason of the high capital costs. VRs not only require experts to install sophisticated irrigation and drainage systems, but also to know how to deal with undesirable wildlife and insects.

1.1.3.4.5 Maintenance: cost and care

The yearly maintenance frequency depends on the type of VRs and plants. EGRs' maintenance is usually rare and affordable but requires at least a yearly checkup to remove undesirable weeds or other plants. However, IGRs necessitate more maintenance because of the deeper growing media and the wide variation of plants. For both types, maintenance should take care of the (1) abduction of weed and unwanted self-sown plants, (2) fertilization and the pruning processes, (3) control of pest and disease (4) adjustment of irrigation especially during dry periods, (5) drainage system, and finally (6) regular inspection for possible leaks.

1.1.3.5 Lebanese vegetative roofs

VRs are recent technologies in Lebanon and could be a fascinating solution for many faced problems. In line with that, Lebanon, a Mediterranean country, leaks a clear sustainability plan as well as an update and management of its infrastructure ever since the civil war (1975-1990). This will definitely lead to road flooding (**Figure 1-10.a**) especially in the urbanized zones amongst other things such as the electricity deficit, air pollution, and the continuous need for a heating/cooling system (**Figures 1-10.b & 1-10.c**) [111-113].

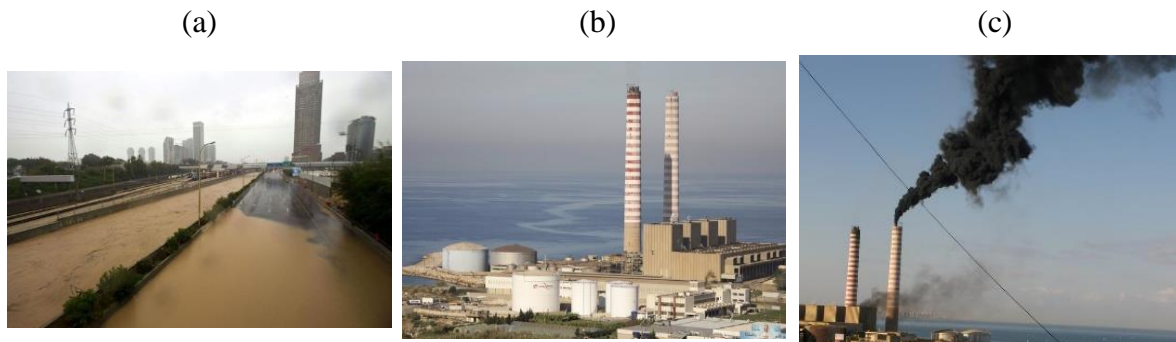


Figure 1-10: Major problems in Lebanon: (a) Road flooding (b) electricity sector (c) air pollution [114-117]

One of the major problems facing Lebanon is the electricity sector. The “Electricité du Liban (EDL)”, a state-owned Lebanese power utility [118], is mandated the responsibility of the generation, transmission, and distribution of electrical energy in Lebanon [119]. In fact, the need for electricity is ensured from thermal and hydraulic power plants, imported from neighboring countries (Syria, Egypt and Turkey) since 2009, and produced by private generators. In 2015, the total energy demand was 20,101.435 GWh, the total energy provided by thermal power plants, hydraulic plants, and private generators was 11,735.29 GWh and the total energy imported from neighboring countries was 3,244.68 GWh. Thus the 2015 energy deficit was 5,121.464 GWh [113, 120-122]. **Figure 1-11** summarizes the situation of the Lebanese power in 2015.

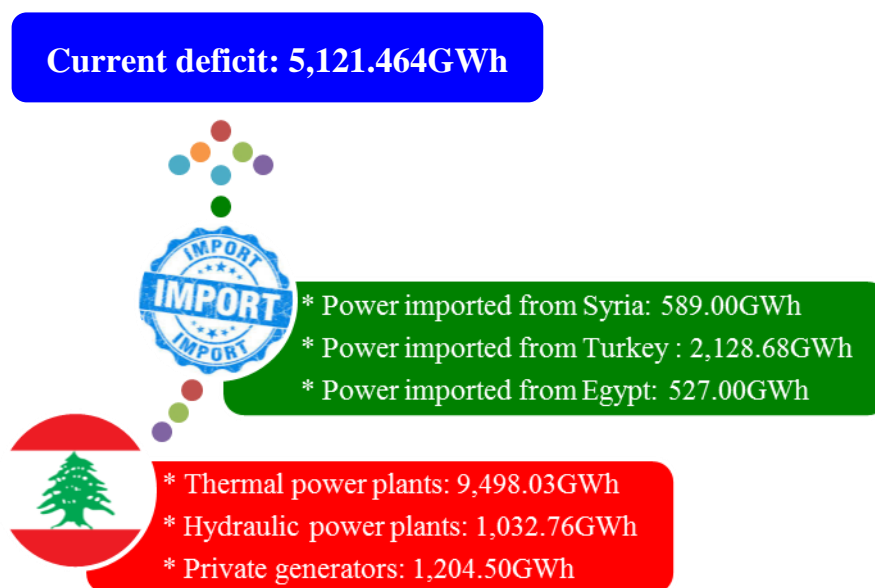


Figure 1-11: Profile of the Lebanese power

Similarly, VRs help to well manage road flooding, which is another serious problem in Lebanon. The increase of impermeable surfaces, especially in urban areas, such as buildings, parking, and roads, could prevent stormwater absorption and lead to road flooding [41, 102]. Water collects pollutants (oil, heavy metals, etc.) and transports them to the underground water [44, 122]. Both the growing medium and the vegetation layer trap and store a large part of the rainfall water to be used by the plants during drought periods, transpired to the atmosphere, or evaporated. In all scenarios, the runoff water is delayed and reduced compared TGBRs [134].

So far, only two EGRs have been installed in Lebanon. The Lebanese VRs are limited to Beirut's first and largest hydroponic roof garden (834 m²) implemented on the headquarter rooftop of the Central Bank of Lebanon and to Batroun's roof garden implemented on the rooftop of a private residential building (200 m²). These two EGRs are displayed in **Figure 1-12** respectively [125, 126].

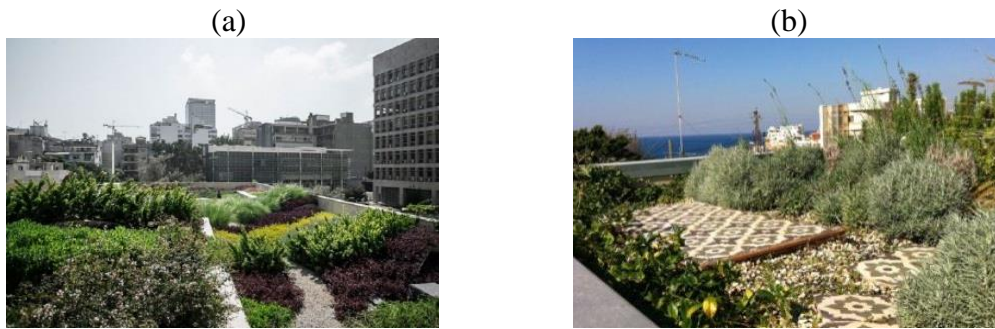


Figure 1-12: VRs on the rooftop of the (a) Lebanese Central Bank, Beirut (b) Casa, Batroun [126, 127]

As described in the text above, VRs offer several advantages. However, in order to determine if VRs are truly superior to TGBRs and WRRs, it was necessary to assess the life cycle perspective, using LCA methodology. This study would enable the determination and the comparison of the potential environmental impacts of TGBR, WRR, EGR, and IGR throughout their life cycle, e.g. from the extraction of the resources until the end-of-life of the roofs. Accordingly, the life cycle assessment methodology is described in the following section.

1.2 Life Cycle Assessment (LCA)

LCA is a technique to evaluate the environmental impacts of a product system from the raw materials extraction phase, passing through the assembly phase and finishing with end of life or disposal phase (**Figure 1-13**). In this perception, the term “product” is normally defined to take account of not only a physical product but also activities, processes and services. Therefore, the term "Life Cycle Assessment" is more accurate than the German one "Okobilanz" or the French one "écobilan" [77].



Figure 1-13: Life cycle of a product [124]

1.2.1 Life Cycle Assessment: history & perspective

1.2.1.1 Past LCA: 1960s–2000s

LCA was known as Life Cycle Analysis in the late 1960s and early 1970s. At that time, it started to be widespread in the United States of America (U.S.A) as well as in Europe (particularly in Germany, England, and Switzerland) [129-133]. Before 1990, LCA was neither attractive to the American public nor well documented while starting 1990 everything was well written.

In 1969, the first modern LCA was generated as stated in Hunt and Franklin. It was done by the Research Institute of Midwest in U.S.A for the benefit of the Coca-Cola Company and focused on the packaging process and the amount of waste. Outputs of this study were not published because of its confidential content [130].

In 1972, the first environmental analysis of a beverage packaging was accomplished by the Institute of Battelle in Frankfurt-Germany [131] and the final report was addressed to the Federal Ministry of Research and Technology.

LCA methodology was criticized due to the lack of guidelines and standards. Therefore, standards appeared between 1997 and 2000: ISO14040 in 1997 [133], ISO 14041 in 1998 [134], ISO 14042 in 2000 [135] and ISO 14043 in 2000 [136]. Currently, these standards are divided in ISO14040 [137] and ISO14044 [138]. Nowadays, LCA is the single internationally standardized method to state the environmental impacts and their consequences [139].

1.2.1.2 Present LCA: 2015s-2016s

In the early days of LCA studies, calculations were performed without using any software or computer. In fact, in 1973, U.S.A used a computer program for the first time to do an LCA study [130]. At the moment, there are lot of calculation software such as LEGEP [140], SBS-online tool [141], GaBi [142], and SimaPro [143]. These programs help researchers to conduct an LCA study and state the potential environmental impacts of a product during its whole Life Cycle.

1.2.2 Phases of Life Cycle Assessment

According to ISO standards, there are four phases to consider when conducting an LCA: goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle

interpretation (**Figure 1-14**). These phases are briefly described in the following sections. Details can be found in **appendix A**.

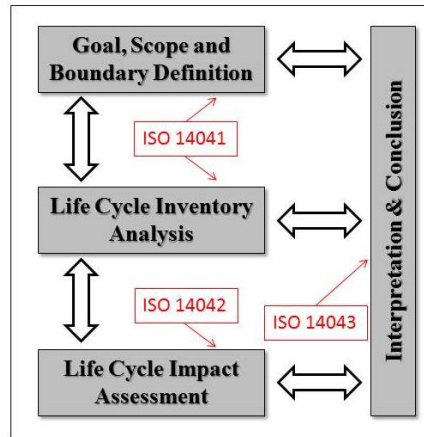


Figure 1-14: ISO-LCA approach [131]

1.2.2.1 Goal and Scope definition (G&SD)

The Goal and Scope Definition (G&SD) is the first and very essential stage in any LCA study. It determines the reasons for carrying out the study as well as the extent of the study. Defining the goal and scope seems to be short and easy but in fact it is very crucial step because it highly affects the LCA results [145]. The goal definition determines the requirements and the level of sophistication of the study. In addition, the results in some cases could be dedicated for both public and private sectors. Thus, the double usage should be clearly defined from the beginning. In the scope of an LCA study, assumptions, limitations, and borders of the assessment are set. While describing the scope of an LCA study, many items shall be considered and clearly designated such as function, functional unit, reference flow, system boundaries, unit process, product system, and required data.

According to the European Environmental Agency (EEA), the functional unit should consider three aspects: the efficiency of the product, the durability of the product, and the performance quality standard [146].

1.2.2.2 Life Cycle Inventory analysis (LCI)

Life Cycle Inventory (LCI) is the second and heaviest phase in an LCA study. It implicates collecting data and calculating procedures to create inputs (raw materials and energy) as well as outputs (emissions to air, water, and soil). These inputs and outputs are for each process included in the boundaries of the product system. The inventory list, known as inventory table

or eco-balance of a product, is a long list of material and energy necessities, products and co-products as well as wastes [147].

The complexity of this step lies in the quality and the availability of data which will highly affect the accuracy of the impact assessment [148]. When data are unavailable or variable, assumptions and estimations become a necessity and are tested using the sensitivity analyses. System modeling and inventory calculations are accomplished using many software namely SimaPro [143] and GABI [142]. Although SimaPro database (Ecoinvent v3.0) covers over 10 000 processes [149], few processes or materials will not be available. Therefore, while collecting the missing data, a distinction should be made between two types of data [150]:

- Foreground data

Foreground data are delivered straight from industry for designating an exact product system or a particular production structure. This data also refers to specific data needed to model the system.

- Background data

Background data are available in SimaPro databases and literature describing the production of generic materials, energy, transport and waste management.

1.2.2.3 Life Cycle Impact Assessment (LCIA)

1.2.2.3.1 Principles of Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) is the third phase in an LCA study. The LCIA methodologies link the LCI results to the corresponding environmental impacts (emissions, waste generation, resource extractions, etc.) by using the characterization factors [138, 151].

ISO 14044 classified the LCI results into impact categories (category midpoints) where each category is correlated to a category indicator. The category indicator is situated at an intermediate point between the LCI results and the damage categories (category endpoints) on the impact track [136].

1.2.2.3.2 IMPACT 2002+

IMPact Assessment of Chemical Toxics (IMPACT 2002+) is an LCIA methodology initially developed at the Swiss federal institute of Technology-Lausanne. As shown in **Figure 1-15**, LCI results are linked to four damage categories via 14 impact categories at midpoint level,

also called midpoint categories. The “damage impact score” or frequently named “damage category” represents the changes of the environment quality.

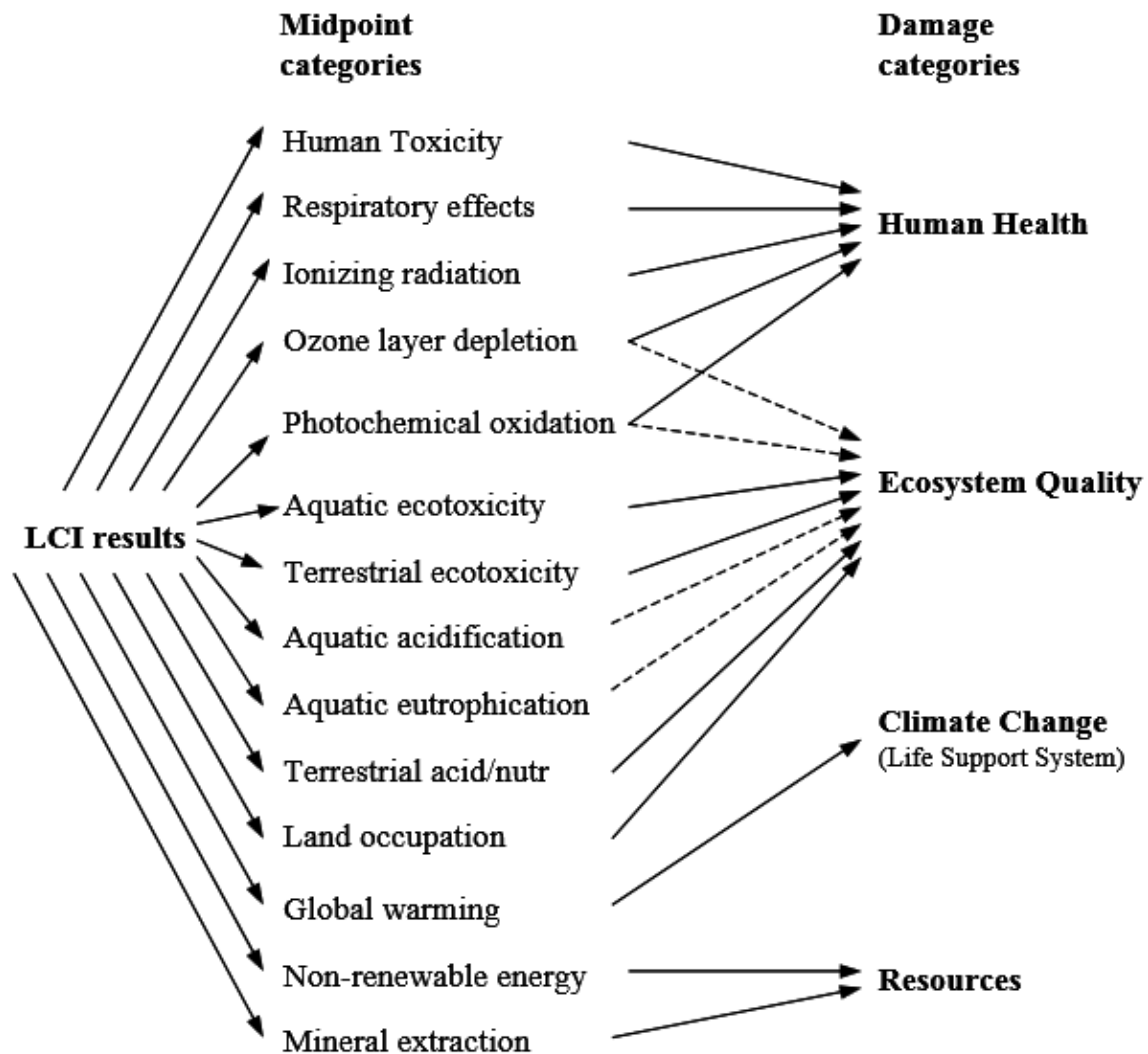


Figure 1-15: General structure of the LCIA framework [152]

In the midpoint categories, carcinogenic and non-carcinogenic effects might be grouped in the “human toxicity” midpoint category. Furthermore, as the respiratory effects are due to inorganics emission, this midpoint category could be called “respiratory inorganics”. Lined arrows symbolize the quantitatively modeled impact pathways while the dotted arrows symbolize the uncertain currently available information between midpoint and damage levels due to missing knowledge or still being in the development phase.

1.2.2.4 Life Cycle Assessment and Interpretation (LCAI)

The Life Cycle Assessment and Interpretation (LCAI) is the last stage in an LCA study. Upon ISO 14044, it is the combination and evaluation of the LCI and LCIA results in order to reach

conclusions, limitations and recommendations. This is accomplished by evaluating the sensitivity and uncertainty analyses of significant data elements as well as assessing the completeness and consistency of the study [139, 153].

1.2.3 Types of life cycle assessment

The previous two subsections explain well a product's life cycle including all stages from raw material acquisition to manufacturing, distribution, use/reuse, maintenance, recycling, ending up with the disposal stage of the product at the end of its life. However, the consideration or not of all these stages in an LCA study, differentiate between cradle to grave and cradle to gate LCA.

1.2.3.1 Cradle-to-grave LCA

A “cradle to grave” approach is a full LCA study from raw material extraction phase which is the “cradle” phase to the disposal phase which is the “grave” phase. In this case, all inputs and outputs are considered for all the phases of the product's life cycle [154-156].

1.2.3.2 Cradle-to-gate LCA

A “cradle to gate” approach is a partial LCA study from raw material extraction phase which is the “cradle” phase to the finished production phase which is the “gate” phase. In this case, the use and the disposal phases of a product are excluded [154, 156].

The environmental impacts in a cradle to gate study are mainly due to the raw materials and to the system constituents (different roofing layers in our case). However, the use and the disposal phases, in a cradle to grave study, influence impressively on the sustainability performance of a product because these phases are contributing to save and/or to create energy as well as avoiding carbon emission and saving resources at the end of life [157].

1.2.4 Lebanese life cycle assessment

LCA approach is a recent domain for the Lebanese researches and until these days some points are still not very well known. As shown in **Figure 1-16**, the published articles in all journals listed in Science Direct database and in journal of Cleaner production. With regards to “Life Cycle Assessment” and “Lebanon” in “All Fields” category, there was 57 online papers in all Science Direct database including only 7 papers in the database “Journal of Cleaner Production” for a period of time ranging from 2000 to date.

A further look into the figure shows that, in last two years, researchers are displaying more interest in analyzing LCA of buildings or renewable technologies [120, 158, 159]. For instance, LCA study to illustrate the environmental effects of the current Lebanese electricity system and a comparative LCA study of monocrystalline photovoltaic system with fossil energy production system [120, 158]. However, none of the 57 published papers elaborates the LCA of a VR in Lebanon. Correspondingly, the LCA study presented in this manuscript is the first of its kind in literature.

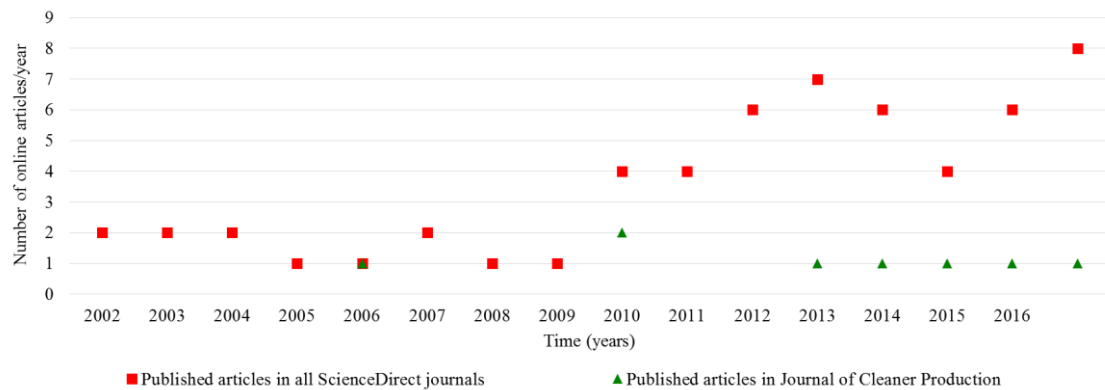


Figure 1-16: Published articles in all Science Direct journals and in journal of Cleaner production with respect to “Life Cycle Assessment” and “Lebanon” in “All Fields” category.

The originality of this research work lies in assessing the environmental impacts, thermal profile, and water management performance of vegetative roofs using LCA approach, real-time temperature monitoring, and real-time soil moisture monitoring, respectively thus addressing a new environment in which only a few studies in the Middle East, if any, have used similar methods. The main originality however is in the constitution of the vegetative roofs’ mockups. In line with that, this study could enlighten policy/decision makers by providing an additional tool or trying to adopt the concept utilized in the construction of green buildings (laws, loans, insurance, etc.). This research, a first of its kind in Lebanon, focuses on:

- i) Analyzing and comparing the environmental impacts of TGBRs, WRRs, EGRs, and IGRs of 834m² and for 45 years,
- ii) Analyzing and characterizing the temperature profile of one TGBR mockup and two EGR mockups that differ by the composition and the depth of the substrate in winter season,
- iii) Establishing a full economic study of EGR compared to TGBR,

- iv) Investigating and depicting the moisture profile of one TGBR mockup and two EGR mockups that differ by the roof slope, the composition, and the depth of the substrate during the winter season,
- v) Analyzing the quality of the runoff water from TGBR and EGR mockups through chemical tests.

1.3 References

- [1] Sustainable development. (2016). Retrieved from <http://www.gdrc.org/sustdev/definitions.html>
- [2] Liu, K., & Baskaran, B. (May 29-30, 2003). Thermal performance of green roofs through field evaluation. (No. NRCC-46412). Ottawa, Canada: National Research Council, Institute for Research in Construction.
- [3] Wong, N. H., Chen, Y., Ong, C. L., & Sia, A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, 38(2), 261-270. doi: [http://dx.doi.org/10.1016/S0360-1323\(02\)00066-5](http://dx.doi.org/10.1016/S0360-1323(02)00066-5)
- [4] Osmundson, T. (1999). *Roof gardens: History, design, and construction* (Norton books for architects & designers) W. W. Norton & Company.
- [5] Sabre, M., & Bulteau, G. (2011). *Végétaliser les toitures et terrasses*. Pour La Science, 403
- [6] Liberty Pumps Inc. (2009). A new look at ballasted roofs. Retrieved from http://www.waterproofmag.com/downloads/2011-01/WP_2011-01_Ballasted-Roofs.pdf
- [7] Weiller, S., & Scholz-Barth, K. (Eds.). (2009). *Green roof systems: A guide to the planning, design, and construction of landscapes over structure* Wiley.
- [8] Ricketts, J. T., Loftin, M. K., & Merritt, F. S. (Eds.). (2004). *Standard handbook for civil engineers* (Fifth Edition ed.) McGraw-Hill.
- [9] Juozapaitis, A., Vainiūnas, P., Zavadskas, E. K., Jonaitis, B., & Zavalis, R. (2013). Modern building materials, structures and techniques experimental research of hollow concrete block masonry stress deformations. *Procedia Engineering*, 57, 473-478. doi: <http://dx.doi.org/10.1016/j.proeng.2013.04.061>
- [10] Ranganath, D. R. V. Ready mix concrete. Retrieved from http://elearning.vtu.ac.in/12/enotes/Adv_Conc_Stru/Unit5-RVR.pdf
- [11] Mastic Asphalt Council. (2015). Ten reasons to choose mastic asphalt. Retrieved from <http://www.masticasphaltcouncil.co.uk/news/ten-reasons-to-choose-mastic-asphalt/>
- [12] Asphaltech Waterproofing. (2012). Polymer modified mastic asphalt. Retrieved from <http://asphaltech.co.nz/products/>

- [13] M&S Roofing. (2015). Mastic asphalt roof system. Retrieved from <http://msroofing.ie/services/mastic-asphalt-roof/>
- [14] Dow Building Solutions. (2015). Insulation boards. Retrieved from <http://building.dow.com/en-us/products>
- [15] Zinco-Canada Inc. (2015). Filter sheets. Retrieved from <http://zinco.ca/filter.html>
- [16] Growing green guide. (2014). The Growing green guide: A guide to green roofs, walls and facades in Melbourne and Victoria. Retrieved from www.growinggreenguide.org
- [17] Sika-Trocal Roofing. Single ply roofing membranes for ballasted roofs. Retrieved from http://gbr.sika.com/dms/getdocument.get/a1af3af9-2cbb-3f4f-88fc-db78d9bebbaf/Sika_Trocal_Ballasted_Roofs.pdf
- [18] Desjarlais, A. O., Petrie, T. W., Atchley, J. A., Gillenwater, R., SynTec, C. & Roodvoets, D. (2008). Evaluating the energy performance of ballasted roof systems. Retrieved from <https://www.spri.org/pdf/Thermal%20Performance%20of%20Ballast%20Study%20Final%20Report%2005%2008%20.pdf>
- [19] Rosenfeld, A. H., Boyd, J. D., Byron , J. D. & Douglas, K. (2008). building energy efficiency standards. Retrieved from <http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF>
- [20] Stewart R. (Ed.). (1985). Methods of satellite oceanography The Royal Institute of Navigation. doi: <http://dx.doi.org/10.1017/S0373463300000229>
- [21] D'Annunzio J-A. (2016). Roofing articles. Retrieved from <http://www.facilitiesnet.com/roofing/articles.asp?sort=recent>
- [22] She, N., & Pang, J. (2009). Physically based green roof model. Journal of Hydrologic Engineering, 15(1084-0699) doi: [http://dx.doi.org/10.1061/\(ASCE\)HE.1943-5584.0000138](http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000138)
- [23] bca.gov.sg. (2015). Waterproofing of reinforced concrete flat roof. Retrieved from <http://www.bca.gov.sg/Publications/EnhancementSeries/others/design2Ch12.pdf>
- [24] Tim, C. (2016). Membrane roofing for flat roofs. Retrieved from <http://www.askthebuilder.com/membrane-roofing-for-flat-roofs-/>
- [25] Roof coatings manufacturers association. (2012). Cold-applied adhesives for modified bitumen membrane roofing.

- [26] Siplast. (2013). White reflective bituminous waterproofing membrane for cool roof. Retrieved from <http://www.siplast-international.com/Sun-Activ/275>
- [27] Siplast. (2015). Roofing. Retrieved from <http://www.siplast.com>
- [28] Cool roofs are ready to save energy, cool urban heat islands, and help slow global warming. Retrieved from http://www1.eere.energy.gov/buildings/pdfs/cool_roof_fact_sheet.pdf
- [29] Chao, J. (2012). Parking lot science: Is black best? Retrieved from <http://newscenter.lbl.gov/2012/09/13/parking-lot-science/>
- [30] Duro-Last roofing, Inc. (2016). The duro-last cool zone® white roof system. Retrieved from http://duro-last.com/white_roofing
- [31] Jacobson, M. Z., & Ten Hoeve, J. E. (2012). Effects of urban surfaces and white roofs on global and regional climate. *Journal of Climate*, (25), 1028–1044. doi: 10.1175/JCLI-D-11-00032.1
- [32] Yaghoobian, N., & Kleissl, J. (2012). Effect of reflective pavements on building energy use. *Urban Climate*, 2, 25-42. doi: <http://dx.doi.org/10.1016/j.uclim.2012.09.002>
- [33] Akbari, H., Menon, S., & Rosenfeld, A. (2008). Global cooling: Increasing world-wide urban albedos to offset CO₂. 94(3), 275–286. doi: 10.1007/s10584-008-9515-9
- [34] Liu, K. Y., & Baskaran, A. (Sept. 2005). Using garden roof systems to achieve sustainable building envelopes.
- [35] Liu, K., & Baskaran, B. (May 29-30, 2003). Thermal performance of green roofs through field evaluation. (No. NRCC-46412). Ottawa, Canada: National Research Council, Institute for Research in Construction.
- [36] Lawson, T. (2015). On rooftops of Paris, expect green roofs and solar panels. *Yes! Magazine*,
- [37] Eumorfopoulou, E., & Aravantinos, D. (1998). The contribution of a planted roof to the thermal protection of buildings in Greece. *Energy and Buildings*, 27(1), 29-36. doi: [http://dx.doi.org/10.1016/S0378-7788\(97\)00023-6](http://dx.doi.org/10.1016/S0378-7788(97)00023-6)
- [38] Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, 42(10), 1582-1591. doi: <http://dx.doi.org/10.1016/j.enbuild.2010.05.004>

- [39] HKU Building Services Engineering. (2013). Green roof research (including vertical greening). Retrieved from www.mech.hku.hk/bse/greenroof/
- [40] Soprema. (2016). Sopranature-green roofing system. Retrieved from <http://www.soprema.ca/en/content/10/sopranature.aspx>
- [41] Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. *Hort Science*, 41(5), 1276-1285.
- [42] Zinco-Canada Inc. (2011). Drainage elements. Retrieved from <http://zinco.ca/drainage.html>
- [43] Getter, K. L., Rowe, D. B., & Andresen, J. A. (2007). Quantifying the effect of slope on extensive green roof stormwater retention. *Ecological Engineering*, 31(4), 225-231. doi: <http://dx.doi.org/10.1016/j.ecoleng.2007.06.004>
- [44] Teemusk, A., & Mander, Ü. (2007). Rainwater runoff quantity and quality performance from a green roof: The effects of short-term events. *Ecological Engineering*, 30(3), 271-277. doi: <http://dx.doi.org/10.1016/j.ecoleng.2007.01.009>
- [45] Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R., Doshi, H., Dunnett, N., ... Rowe, B. (November 2007). Green roofs as urban ecosystems: Ecological structures, functions, and services. *Bioscience*, 57(10), 823-833. doi: 10.1641/B571005
- [46] Alexander, R. (2004). Green roof grow with brown compost. *Biocycle*, 54-56.
- [47] Friedrich, C. R. (4-6 May 2005). Principles for selecting the proper components for a green roof growing media. In *Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Washington, DC., 262-273.
- [48] Sailor, D. J., Hutchinson, D., & Bokovoy, L. (2008). Thermal property measurements for ecoroof soils common in the western U.S. *Energy and Buildings*, 40(7), 1246-1251. doi: <http://dx.doi.org/10.1016/j.enbuild.2007.11.004>
- [49] Zinco-Canada Inc. (2011). Root barriers & slip sheets. Retrieved from <http://zinco.ca/rootbarrier.html>
- [50] Jim, C. Y., & Tsang, S. W. (2011). Biophysical properties and thermal performance of an intensive green roof. *Building and Environment*, 46(6), 1263-1274. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.12.013>

- [51] Villarreal, E. L., & Bengtsson, L. (2005). Response of a sedum green-roof to individual rain events. *Ecological Engineering*, 25(1), 1-7. doi: <http://dx.doi.org/10.1016/j.ecoleng.2004.11.008>
- [52] Organic chicken manure fertilizer. (2015). Retrieved from <http://www.triferto.eu/Userfiles/files/organic-boost-npk-4-3-3-triferto.pdf>
- [53] Cuttings. (2011). Retrieved from http://zinco.ca/Products/ZinCo_PDB_Sedum_Cuttings_engl.pdf
- [54] Blankets. (2011). Retrieved from http://zinco.ca/Products/ZinCo_PDB_Pre-cultivated_Vegetation_Mats_engl.pdf
- [55] Blankets. (2015). Retrieved from <https://www.sempergreen.com/us/products/vegetation-blanket>.
- [56] Czemieli Berndtsson, J. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, 36(4), 351-360. doi: <http://dx.doi.org/10.1016/j.ecoleng.2009.12.014>
- [59] Green roofs. (2013). Retrieved from <http://www.epa.gov/heatisld/mitigation/greenroofs.htm>
- [60] Peck, S., & M, K. (2003). Design guidelines for green roofs Canada Mortgage and Housing Corporation and the Ontario Association of Architects.
- [61] Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, 77(3), 217-226. doi: <http://dx.doi.org/10.1016/j.landurbplan.2005.02.010>
- [62] Rowe, D. B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution*, 159(8–9), 2100-2110. doi: <http://dx.doi.org/10.1016/j.envpol.2010.10.029>
- [63] Schrader, S., & Böning, M. (2006). Soil formation on green roofs and its contribution to urban biodiversity with emphasis on collembolans. *Pedobiologia*, 50(4), 347-356. doi: <http://dx.doi.org/10.1016/j.pedobi.2006.06.003>
- [64] UNDP human development report 2007/2008. Demographic trends. (2012). (No. 2009).
- [65] Sky Garden Green Roofs. (2015). The history of green roofs. Retrieved from www.sky-garden.co.uk/news/history-of-green-roofs.php

- [66] Stovin, V., Dunnett, N., & Hallam, A. (2007). Green Roofs—getting sustainable drainage off the ground. 6th International Conference of Sustainable Techniques and Strategies in Urban Water Mangement, Lyon, France. 11-18
- [67] Berndtsson, J. C., Bengtsson, L., & Jinno, K. (2009). Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering*, 35(3), 369-380. doi: <http://dx.doi.org/10.1016/j.ecoleng.2008.09.020>
- [68] Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and Environment*, 46(3), 729-738. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.10.006>
- [69] Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, 42(31), 7266-7273. doi: <http://dx.doi.org/10.1016/j.atmosenv.2008.07.003>
- [70] Li, J., Wai, O. W. H., Li, Y. S., Zhan, J., Ho, Y. A., Li, J., & Lam, E. (2010). Effect of green roof on ambient CO₂ concentration. *Building and Environment*, 45(12), 2644-2651. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.05.025>
- [71] Teemusk, A., & Mander, Ü. (2009). Green roof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia. *Building and Environment*, 44(3), 643-650. doi: <http://dx.doi.org/10.1016/j.buildenv.2008.05.011>
- [72] Lin, Y., & Lin, H. (2011). Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. *Building and Environment*, 46(2), 345-355. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.07.027>
- [73] Onmura, S., Matsumoto, M., & Hokoi, S. (2001). Study on evaporative cooling effect of roof lawn gardens. *Energy and Buildings*, 33(7), 653-666. doi: [http://dx.doi.org/10.1016/S0378-7788\(00\)00134-1](http://dx.doi.org/10.1016/S0378-7788(00)00134-1)
- [74] Kosareo, L., & Ries, R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and Environment*, 42(7), 2606-2613. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.06.019>
- [75] Takebayashi, H., & Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment*, 42(8), 2971-2979. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.06.017>

- [76] Banting, D., Doshi, H., Li, J., & Missios, P.,. (2005). Report on the environmental benefits and costs of green roof technology for the city of toronto. City of Toronto and Ontario Centres of Excellence-Earth and Environmental Technologies (OCE-ETech)
- [77] Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, 43(4), 480-493. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.10.055>
- [78] Gomez, F., Gaja, E., & Reig, A. (1998). Vegetation and climatic changes in a city. *Ecological Engineering*, 10(4), 355-360. doi: [http://dx.doi.org/10.1016/S0925-8574\(98\)00002-0](http://dx.doi.org/10.1016/S0925-8574(98)00002-0)
- [79] Teemusk, A., & Mander, Ü. (2010). Temperature regime of planted roofs compared with conventional roofing systems. *Ecological Engineering*, 36(1), 91-95. doi: <http://dx.doi.org/10.1016/j.ecoleng.2009.09.009>
- [80] Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy*, 32(9), 1781-1788. doi: <http://dx.doi.org/10.1016/j.energy.2006.11.011>
- [81] Johnston, J., & Newton, J. (1988). *Building green: A guide to using plants on roofs, walls and pavements* London Ecology Unit.
- [82] Liesecke, H-J.; Krupka, B.; Brueggemann, H. (1989). *Grundlagen der Dachbegruenung, Zur Planung, Ausfuehrung und Unterhaltung von Extensiv begruenungen und Einfachen Intensiv begruenungen*; Patzer Verlag, Berlin - Hannover.
- [83] Liptan, T.,. (May 29–30, 2003). Planning, zoning and financial incentives for ecoroofs in portland, oregon. , Presented in Proceedings of the First North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago The Cardinal Group,Toronto, pp. 113–120.
- [84] Berghage, R., Thuring, C., Beattie, D., Jarrett, A. R., Razaei, F., & O'Connor, T. P. (2009). Green roofs for stormwater runoff control. *Research Gate*, , 81.
- [85] Teemsuk, A., & Mander, U. (2006). In Mander U., Brebbia C. A. and Tiezzi E. (Eds.), *The use of greenroofs for the mitigation of environmental problems in urban areas* National Academy of Sciences.

- [86] Green Roofs for Healthy Cities. (2014). Green roof benefits. Retrieved from <http://www.greenroofs.org/index.php/about/greenroofbenefits>
- [87] Deutsch, B., Whitlow, H., Sullivan, M., & Savineau, A. (2005). RE-GREENING WASHINGTON, DC: A green roof vision based on quantifying storm water and air quality benefits. Casey Trees Endowment Fund Limno-Tech, Inc, , 1-15.
- [88] North American Wetland Engineering, P.A,. (1998). "Ecology, construction, and benefits". ReNature/NAWE Green Roof Product Literature, Minnesota,
- [89] Thompson, W. (1998). Grass-roofs movement. In Landscape Architecture, the Magazine of the American Society of Landscape Architects, 88, 47-51.
- [90] Hooker, J., & Hendriks, N. (1994). The green roofs of europe. The International Waterproofing Association at the 107th Annual Convention and Exhibit of the National Roofing Contractors Association, San Francisco, CA,
- [91] Fountain, M. E., & Arens, E. A. (1993). Air Movement and thermal comfort. Escholarship, , 26-30.
- [92] British Board of Agrément Bucknalls Lane, Watford Herts WD25 9BA. (2012). Air movement & thermal performance. Bba,
- [93] Minke, G., & Witter, G. (Eds.). (1983). Haeuser mit gruenem pelz, ein handbuch zur hausbegruenung Verlag Dieter Fricke GmbH, Frankfurt.
- [94] Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295-310. doi: [http://dx.doi.org/10.1016/S0038-092X\(00\)00089-X](http://dx.doi.org/10.1016/S0038-092X(00)00089-X)
- [95] EPA. (2015). Reducing urban heat islands: Compendium of strategies. Retrieved from <https://www.epa.gov/heat-islands/reducing-urban-heat-islands-compendium-strategies>
- [96] Solecki, W. D., Rosenzweig, C., Parshall, L., Pope, G., Clark, M., Cox, J., & Wiencke, M. (2005). Mitigation of the heat island effect in urban new jersey. Global Environmental Change Part B: Environmental Hazards, 6(1), 39-49. doi: <http://dx.doi.org/10.1016/j.hazards.2004.12.002>

- [97] Li, Y., & Zhao, X. (2012). An empirical study of the impact of human activity on long-term temperature change in china: A perspective from energy consumption. *Journal of Geophysical Research*, 117(D17), 1-12. doi: 10.1029/2012JD018132
- [98] Howard, L. (1818). *The climate of London: Deduced from meteorological observations, made at different places in the neighborhood of the metropolis*. London, 1, 20.
- [99] Wong, N. H., Cheong, D. K. W., Yan, H., Soh, J., Ong, C. L., & Sia, A. (2003). The effects of rooftop garden on energy consumption of a commercial building in Singapore. *Energy and Buildings*, 35(4), 353-364. doi: [http://dx.doi.org/10.1016/S0378-7788\(02\)00108-1](http://dx.doi.org/10.1016/S0378-7788(02)00108-1)
- [100] Kula, R. (2005). Green roofs and the LEED green building rating system, p. 141–153. In *Proc. of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Washington, DC. 4–6 may 2005. the Cardinal Group, Toronto., , 141-153.
- [101] Laberge, K. M. (2003). Urban oasis: Chicago's city hall green roof. In *Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Chicago. 29–30 may 2003. the Cardinal Group, Toronto., , 194-203.
- [102] Feng, C., Meng, Q., & Zhang, Y. (2010). Theoretical and experimental analysis of the energy balance of extensive green roofs. *Energy and Buildings*, 42(6), 959-965. doi: <http://dx.doi.org/10.1016/j.enbuild.2009.12.014>
- [103] Fioretti, R., Palla, A., Lanza, L. G., & Principi, P. (2010). Green roof energy and water related performance in the mediterranean climate. *Building and Environment*, 45(8), 1890-1904. doi:<http://dx.doi.org/10.1016/j.buildenv.2010.03.001>
- [104] Coffman RR, Davis G. (2005). Insect and avian fauna presence on the ford assembly plant ecoroof. Paper Presented at the Third Annual Greening Rooftops for Sustainable Communities Conference, Awards and Trade show; 4–6 may 2005, Washington, DC,
- [105] Brenneisen, S.,. (2006). Space for urban wildlife: Designing green roofs as habitats in switzerland. Retrieved from http://www.urbanhabitats.org/v04n01/wildlife_full.html
- [106] Grant, G. (2006). Extensive green roofs in London. *Urban Habitats*, 4, 51-65.
- [107] Baumann, N. (2006). Ground-nesting birds on green roofs in Switzerland: Preliminary observations. *Urban Habitats*,

- [108] Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science*, 224, 420.
- [109] Banting, D., Doshi, H., Li, J., & Missios, P.,. (2005). Report on the environmental benefits and costs of green roof technology for the city of Toronto. City of Toronto and Ontario Centres of Excellence-Earth and Environmental Technologies (OCE-ETech)
- [110] Carter, T., & Keeler, A. (2008). Life-cycle cost–benefit analysis of extensive vegetated roof systems. *Journal of Environmental Management*, 87(3), 350-363. doi: <http://dx.doi.org/10.1016/j.jenvman.2007.01.024>
- [111] Davies, R. (2013). Floods in Lebanon close Beirut airport road. Floodlist,
- [112] The daily Star. (2013). Beirut airport road reopens after heavy rain flooding.
- [113] Lebanese Republic Ministry of Energy and Water. (2010). Policy paper for the electricity sector. Retrieved from <http://climatechange.moe.gov.lb/viewfile.aspx?id=121>
- [114] The daily star. (2015). Electricity company promises to restore beirut, south lebanon power by Saturday. Retrieved from <http://www.dailystar.com.lb/News/Lebanon-News/2015/Aug-06/309977-electricity-company-promises-to-restore-beirut-south-lebanon-power-by-saturday.ashx>
- [115] Guez, J. (2016). Torrential rain, snow storms and flooding hit the Middle East. Retrieved from http://www.google.com/imgres?imgurl=http://i.telegraph.co.uk/multimedia/archive/02446/israel-tel-aviv-ro_2446266k.jpg&imgrefurl=http://www.telegraph.co.uk/news/picturegalleries/worldnews/9788747/Torrential-rain-snow-storms-and-flooding-hit-the-Middle-East.html&h=536&w=858&tbnid=bfdogz613mbkpM:&docid=J4cc2ajXJtS0XM&ei=LewxVsGIFcisUdevgogF&tbm=isch&ved=0CCcQMygLMAtqFQoTCIHTm5C058gCFUhWFAod15cAUQ
- [116] The daily star. (2011). More than 90 percent of beirut residents exposed to air pollution. Retrieved from http://www.google.com/imgres?imgurl=http://www.dailystar.com.lb/dailystar/Pictures/2011/05/09/exhaust_file_299_634405457868830762_img650x420_img650x420_crop.jpg&imgrefurl=http://www.dailystar.com.lb/News/Local-News/2011/May-09/More-than-90-percent-of-Beirut-residents-exposed-to-air-

pollution.ashx&h=420&w=650&tbnid=H7YWgM21Dl_L3M:&docid=R_aP6ylnCvjggM&ei=Pu0xVqDqIMqrUcmUnagH&tbnid=isch&ved=0CHIQMyhLMetqFQoTCKCBvpK158gCFcpVFAodSUoHdQ

- [117]Erik-Vincenti, Z. (2012). Zouk – power plant vomiting black smoke. Retrieved from <https://bluelebanon.wordpress.com/2012/05/06/turn-off-your-ac-open-your-window/>
- [118]Bank Audi Research. (2012). Zouk power plant. Retrieved from <http://www.projectsmiddleeast.com/Lebanon-NewsArticle-1837#.V1ZhW-S3uW5>
- [119]The European Union. (2012). Paving the way for the Mediterranean solar plan: Lebanon. (No. ENPI 2010/248-486).The European Union
- [120]El-Fadel, R. H., Hammond, G. P., Harajli, H. A., Jones, C. I., Kabakian, V. K., & Winnett, A. B. (2010). The lebanese electricity system in the context of sustainable development. Energy Policy, 38(2), 751-761. doi: <http://dx.doi.org/10.1016/j.enpol.2009.10.020>
- [121]World Bank. (2008). Republic of Lebanon electricity sector public expenditure review. (No. 41421-LB).Sustainable Development Department Middle East and North Africa Region.
- [122]The Lebanese solar energy society. (2011). Solar thermal systems survey for the Lebanese market. Lebanese Market Solar Thermal Systems Survey,
- [123]Jacobsen, B. (2009). Sustainable roofscapes: developing a green roof implementation model for tucson, AZ. Retrieved from <http://wsp.arizona.edu/sites/wsp.arizona.edu/files/uawater/documents/Fellowship200809/Jacobsen.pdf>
- [124]United Nations Development Programme. (2014). Launching of the green roof at the central bank main branch in hamra. Retrieved from <http://www.lb.undp.org/content/lebanon/en/home/presscenter/pressreleases/2014/06/30/launching-of-the-green-roof-at-the-central-bank-main-branch-in-hamra.html>
- [125]Architecture lab. (2014). Central bank of lebanon roof garden, beirut / green studios. Retrieved from <http://architecturelab.net/central-bank-of-lebanon-roof-garden-beirut-green-studios/>
- [126]Building Research Establishment. (2015). Casa batroun, lebanon. Retrieved from <http://www.breeam.com/index.jsp?id=695>

- [128]Scientific Applications International Corporation (SAIC). (2006). Life cycle assessment: Principles and practice.
- [129]Hunt, R., & Franklin, W. (1996). LCA — how it came about. Personal reflections on the origin and the development of LCA in the USA. *The International Journal of Life Cycle Assessment*, 1(1), 4-7.
- [130]B. Oberbacher; H. Nikodem; W. Klopffer. (1996). LCA — how it came about. *The International Journal of Life Cycle Assessment*, 1(1), 4-7.
- [131]Boustead, I. (1996). LCA - how it came about. the beginning in UK. *The International Journal of Life Cycle Assessment*, 1(3), 147-150. doi: 10.1007/BF02978943
- [132]Fink, P. (1997). The roots of LCA in Switzerland - continuous learning by doing. *The International Journal of Life Cycle Assessment*, 2(3), 131-134.
- [133]Environmental management - life cycle assessment - principles and framework (ISO14040 – 1997). (1997). Retrieved from http://www.iso.org/iso/catalogue_detail.htm?csnumber=23151
- [134]Environmental management -- life cycle assessment -- goal and scope definition and inventory analysis (ISO 14041:1998). (1998). Retrieved from http://www.iso.org/iso/catalogue_detail.htm?csnumber=23152
- [135]Environmental management–Life cycle assessment –Life cycle impact assessment (ISO 14042:2000). (2000). Retrieved from http://www.iso.org/iso/catalogue_detail.htm?csnumber=23153
- [136]ISO 14043:2000). (2000). Retrieved from http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_detail_ics.htm?csnumber=23154
- [137]Environmental management -- life cycle assessment -- principles and framework (ISO 14040:2006). (2006). Retrieved from http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=37456
- [138]Environmental management–Life cycle assessment –Requirements and guidelines (ISO 14044:2006). (2006). Retrieved from http://www.iso.org/iso/catalogue_detail?csnumber=38498

- [139] Klöpffer, W., & Grahl, B. (2012). *Ökobilanz (LCA)*. Weinheim: Wiley-VCH.
- [140] LEGEP. Homepage LEGEP-software. Retrieved from <http://www.legep.de/>
- [141] SBS Building Sustainability. Homepage SBS-online tool-software. Retrieved from <https://www.sbs-onlinetool.com>
- [142] GaBi. Homepage GaBi-software. Retrieved from <http://www.gabi-software.com>
- [143] SimaPro. Homepage SimaPro-software. Retrieved from www.simapro.com
- [144] Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling*, 74, 101-114. doi: <http://dx.doi.org/10.1016/j.resconrec.2013.02.018>
- [145] Lindfors, L., Christiansen, K., Hoffmann, L., Virtanen, Y., Juntilla, V., Hanssen, O., . . . Finnveden, G. (1995c). *Nordic guidelines on life-cycle assessment*. Copenhagen: Nordic Council of Ministers.
- [146] Guinée, J., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., van Oers, L., . . . Huijbregts, M. (2002). *Life cycle assessment: an operational guide to the ISO standards*. The Netherlands,
- [147] EPA. (1995). *Life-cycle impact assessment: A conceptual framework, key issues, and summary of existing methods*. (No. EPA/452/R-95/002). Ohio, U.S.A: Environmental Protection Agency.
- [148] Goedkoop, M., Schryver, A. N. & Oele, M. (2007). *Introduction to LCA with SimaPro 7*. Retrieved from <http://web.stanford.edu/class/cee214/Readings/SimaPro7Tutorial.pdf>
- [149] Ecoinvent Centre. (2012). Ecoinvent centre portal. Retrieved from <http://www.ecoinvent.org/home/>
- [150] Ekval, T. Guidance notes on tools for POLLUTION MANAGEMENT. (Note). The World Bank.
- [151] Jolliet, O., Brent, A., Goedkoop, M., Itsubo, N., Mueller-Wenk, R., Peña, C., . . . Weidema, B. (2003a). *LCIA definition study of the SETAC-UNEP life cycle initiative*. (). UNEP
- [152] Skone, T. J. (2000). What is life cycle interpretation?. *Environmental Progress & Sustainable Energy*, doi: 10.1002/ep.670190207

- [153] Han, H., Oneil, E., Bergman, R. D., Eastin, I. L., & Johnson, L. R. (2015). Cradle-to-gate life cycle impacts of redwood forest resource harvesting in northern California. *Journal of Cleaner Production*, 99, 217-229. doi: <http://dx.doi.org/10.1016/j.jclepro.2015.02.088>
- [154] Hervy, M., Evangelisti, S., Lettieri, P., & Lee, K. (2015). Life cycle assessment of nanocellulose-reinforced advanced fibre composites. *Composites Science and Technology*, 118, 154-162. doi: <http://dx.doi.org/10.1016/j.compscitech.2015.08.024>
- [155] Winter, M., Ibbotson, S., Kara, S., & Herrmann, C. (2015). Life cycle assessment of cubic boron nitride grinding wheels. *Journal of Cleaner Production*, 107, 707-721. doi: <http://dx.doi.org/10.1016/j.jclepro.2015.05.088>
- [156] Espinosa, N., Serrano-Luján, L., Urbina, A., & Krebs, F. C. (2015). Solution and vapour deposited lead perovskite solar cells: Ecotoxicity from a life cycle assessment perspective. *Solar Energy Materials and Solar Cells*, 137, 303-310. doi: <http://dx.doi.org/10.1016/j.solmat.2015.02.013>
- [157] Kabakian, V., McManus, M. C., & Harajli, H. (2015). Attributional life cycle assessment of mounted 1.8 kWp monocrystalline photovoltaic system with batteries and comparison with fossil energy production system. *Applied Energy*, 154, 428-437. doi: <http://dx.doi.org/10.1016/j.apenergy.2015.04.125>
- [158] Stephan, A., & Stephan, L. (2014). Reducing the total life cycle energy demand of recent residential buildings in Lebanon. *Energy*, 74, 618-637. doi: <http://dx.doi.org/10.1016/j.energy.2014.07.028>
- [159] Jolliet O, Margni M, Charles R, Humbert S, Jérôme P, Rebitzer G, and Rosenbaum R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *Int J LCA* 8(6): 324-330.

CHAPTER 2 OBJECTIVES AND METHODOLOGY

The literature review identified several gaps concerning VRs particularly in the Mediterranean region. Some of which will be addressed in this research, including:

- 1) An environmental assessment and comparison of TGBR, WRR, EGR, and IGR,
- 2) A real-time temperature monitoring at different substrate depths to estimate the heating/cooling demand of a Lebanese residential building during winter season,
- 3) A water management and runoff water quality assessment of TGBR and EGR in the Lebanese Mediterranean winter season.

This chapter provides insight to the research hypotheses and objectives of this study. An introduction is provided for the accepted/submitted manuscripts. Lastly, the followed methodological steps to confirm or reject research hypotheses are elaborated in the sections below.

2.1 Research hypotheses and objectives

2.1.1 Research hypotheses

While mapping major problems in Lebanon to the advantages of using VRs, one can easily depict an absolute harmony. Hence, the aim of this research is to confirm numerically and experimentally the following hypotheses:

- EGR reduces temperature fluctuation of base roof membrane leading to a decline in the heating/cooling demand compared to TGBR,
- EGR is more environmental friendly than TGBR, WRR, and IGR; in addition, EGR improves runoff water quality compared to TGBR.

2.1.2 Objectives

The aim of this research is to:

- 1- Evaluate and compare potential environmental impacts of TGBR, WRR, EGR, and IGR through the LCA approach (1st manuscript),
- 2- Draw the thermal profile through a real-time temperature monitoring of TGBR compared to EGR at different substrate depths along with an estimate heating/cooling demand of a 200m² residential building (2nd manuscript),

- 3- Assess, for both TGBR and EGR, the water management through a real-time soil moisture monitoring and the runoff water quality through chemical tests (3rd manuscript).

2.2 Introduction of the manuscripts

The first manuscript presents a cradle-to-gate life cycle assessment study followed by a sensitivity and uncertainty analyses on a real EGR of 834m² installed at the Central bank of Lebanon and on three fictitious roofs of the same area: TGBR, WRR, and IGR. Results indicated that EGR had the least potential environmental impacts for most of the 15 impact categories considered. The first manuscript entitled “*Cradle-to-gate life cycle assessment of traditional gravel ballasted, white reflective, and vegetative roofs: a Lebanese case study*” is published in “**Cleaner Journal of Production**”.

The second manuscript attempts to evaluate and compare energy performance and heating/cooling demand of TGBR and EGR. Temperature profiles were drawn based on a real-time temperature monitoring of a TGBR and two EGR mockups installed at the rooftop of the Chemical Engineering Department at the University of Balamand. EGR mockups differed in depth and composition of substrate. In this study, temperature profiles clearly indicated the reduction of temperature fluctuations under substrate layer, heat storage effect, and passive cooling effect even for sunny winter day ($T_{air\ max} = 32^{\circ}C$). Moreover, the economic study showed that EGRs could save up to 45USD/200m²/month compared to TGBRs. The second manuscript entitled “*Real-time temperature monitoring for traditional gravel ballasted roof and an extensive green roof: A Lebanese case study*” has accepted in “**Energy and Buildings**”.

The third manuscript conducts an evaluation and comparison of water management and runoff water quality of TGBR and EGRs. The vertical soil moisture profile was drawn based on a real-time soil moisture monitoring of TGBR and EGRs mockups installed at the rooftop of the Chemical Engineering Department at the University of Balamand. EGR mockups differed in the roof slope, the depth, and the composition of the substrate. In fact, EGR8 and EGR16 delay and reduce runoff water compared to TGBR acting as a sink for cadmium, iron, calcium, and ammonium. The third manuscript entitled “*Performance of extensive green roofs towards runoff water quantity and quality: A Lebanese case study*” has been submitted in the “**Ecological Engineering**” journal.

2.3 General methodology

Figure 2-1 provides the general methodology adopted to reach the objectives and to test the research hypotheses.

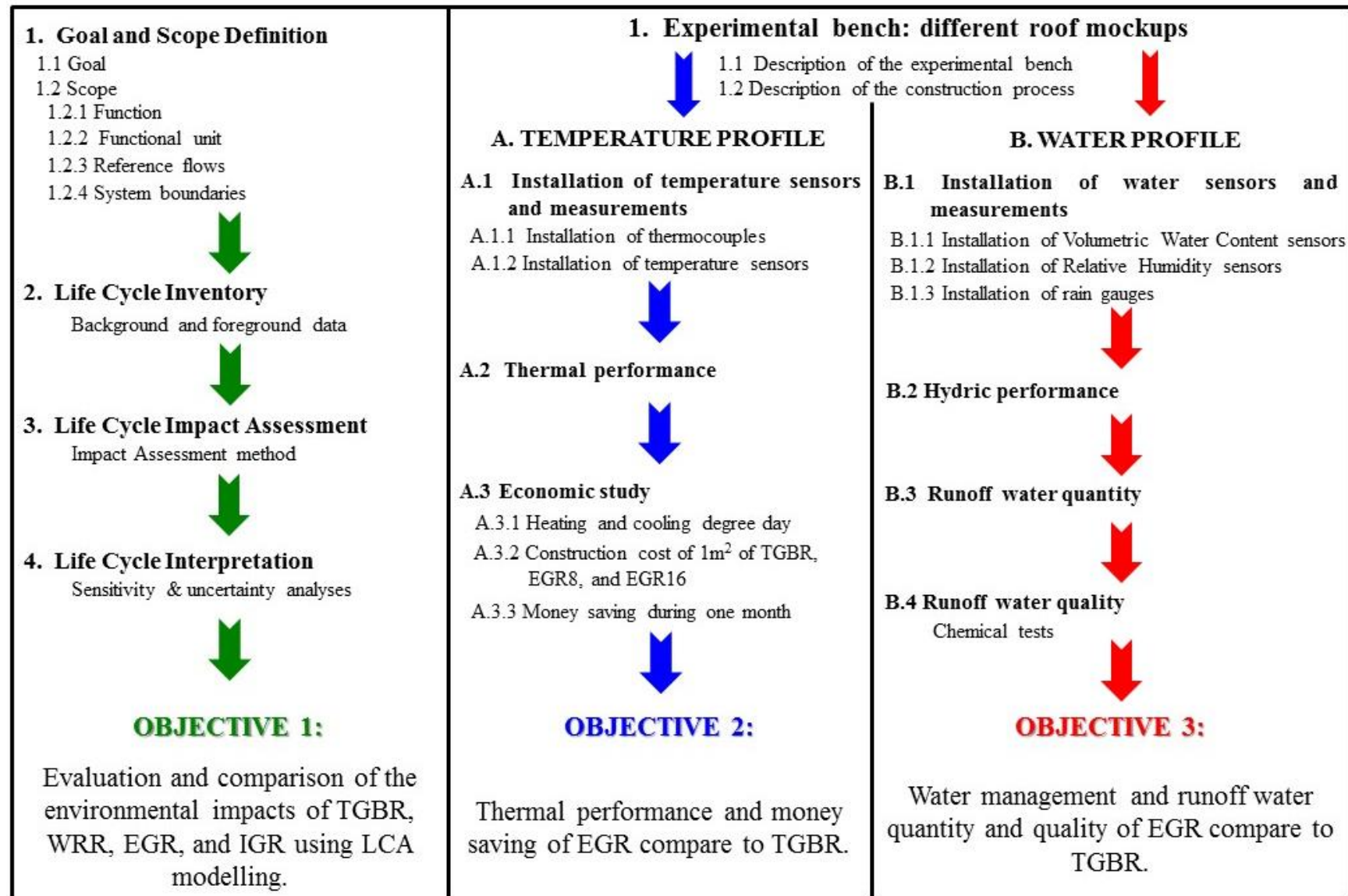


Figure 2-1: Objectives of the study

The following sub-sections explore, in detail, each of the steps followed for the completion of the three manuscripts.

2.4 Evaluation and comparison of environmental impacts using LCA approach

The life cycle of a product, particularly of VRs, is essential especially from an environmental perspective. Its importance lies in the additional layers of VR compared to the ones of TGBR. At the same time, these additional layers are source of environmental advantage.

The environmental impacts were stated based on a comparative LCA on a real EGR of 834m² installed at the Central bank of Lebanon, Hamra branch (**Figure 2-2**) and on three fictitious roofs of the same area: TGBR, WRR, and IGR.

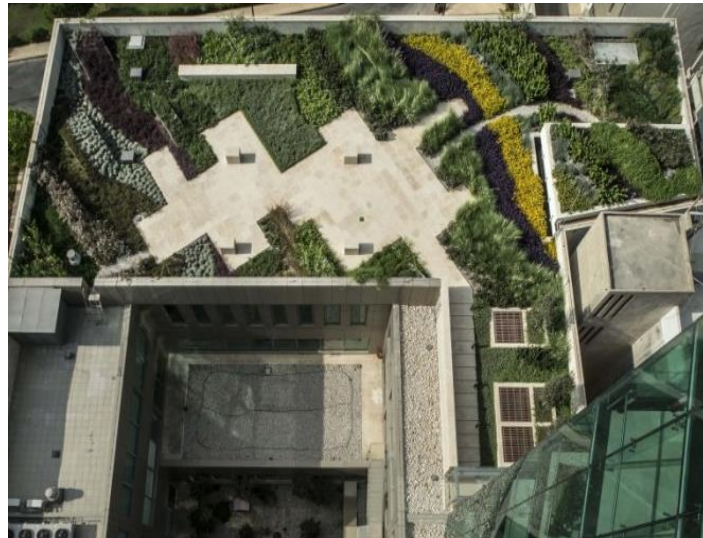


Figure 2-2: View from the top of the EGR at the Central Bank of Lebanon

2.4.1 Goal and Scope Definition

2.4.1.1 Goal

The goal of this study is to analyze and compare the environmental impacts of TGBR, WRR, EGR, and IGR of 834m² and for 45 years.

2.4.1.2 Scope

2.4.1.2.1 Function

The function of each roof is: covering a certain surface area for a specific amount of time.

2.4.1.2.2 Functional unit

The Functional Unit is a quantification of the function of product. In this study, the FU used for the comparison is the following: “the installation of a roofing system to cover a surface of 834m² for a period of 45 years”.

2.4.1.2.3 Reference flows

The reference flows are the quantity of each of the compared products required to satisfy the studied FU. These are very important to be identified in order to have a fair comparison. In fact, to determine the reference flows, the lifetime of the roofs is a key parameter. The lifespan of TGBR, WRR, and VRs was assumed to be 15, 30, and 45 years, respectively [1,2]. Therefore, the reference flows were:

- 3.0 for TGBR (45 years/15-year lifespan),
- 1.5 for WRR (45 years/30-year lifespan),
- 1.0 for EGR (45 years/45-year lifespan),
- 1.0 for IGR (45 years/45-year lifespan).

This means that, to fulfill the functional unit, the comparison should be made between 3 TGBR, 1.5 WRR, 1 EGR, and 1 IGR. In particular, for each roof type, all inputs and outputs for each unit process considered in the life cycle were multiplied by its respective reference flow.

2.4.1.2.4 System Boundaries

For TGBR (**Figure 2-3.a**), the considered layers are as follows: roof assembly, thermal insulation layer (Polystyrene), waterproof membrane (Polyester), filter sheet (Polypropylene), and an exterior layer made of pebbles. The roof assembly was modelled as a mixture of hollow concrete blocks (sand-lime brick), rebar and concrete, while the waterproof layer was modelled as mastic asphalt.

WRR (**Figure 2-3.b**) is made of the following layers: roof assembly, thermal insulation membrane, waterproof layer (Polyester), and white reflective membrane (Polyester). The roof assembly was the same for TGBR while the waterproof membrane was an SBS modified bitumen membrane, and the thermal insulation layer was a rock wool blanket.

As for VRs (**Figure 2-3.c**), the following layers were taken into consideration: roof assembly, thermal insulation layer, waterproof membrane, root resistant barrier (Polyethylene), drainage

layer (Polyethylene), filter sheet (Polypropylene), and growing medium. The roof assembly and the waterproof membrane were the same as for WRR. The substrate was 15.0 cm depth for EGR and assumed to be 120.0 cm depth for IGR. Upon the technicians of the United Nations Development Program (UNDP), Country Energy Efficiency and Renewable Energy Demonstration for the recovery of Lebanon (CEDRO) project, EGR substrate was consisting of sand (55.0 %), pozzolan (17.5 %), perlite (17.5 %), and organic fertilizer (10.0 %), thus the IGR substrate was assumed to have the same composition.

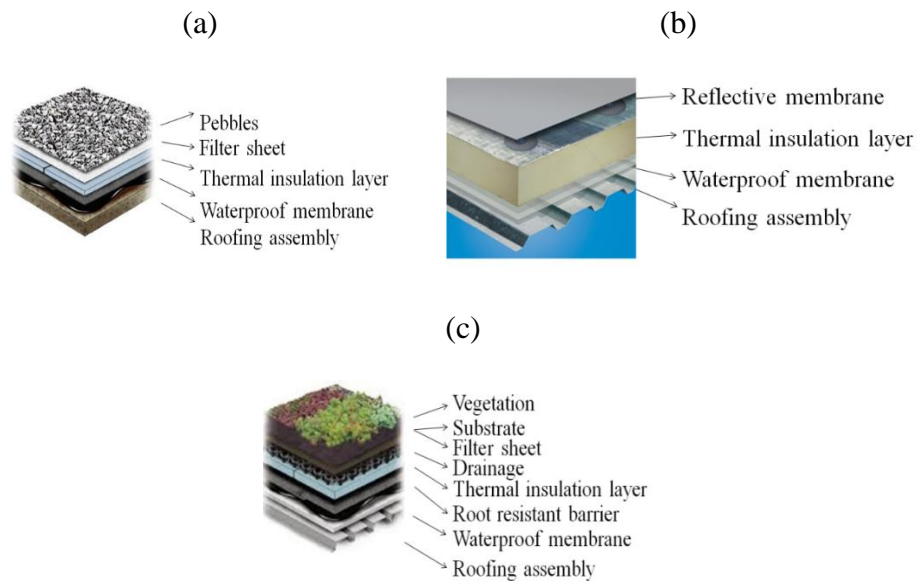


Figure 2-3: (a) TGBR (b) WRR (c) VR

A cradle-to-gate LCA study was performed. In particular, inputs and outputs from raw materials extraction to the assembly were considered, including energy and transport needed for these two phases. Therefore, the use and the end of life phases were not taken into account in this study. Plants were not present in the database of the used software consequently the vegetation layer of VRs was not modeled. The boundaries of the LCA study are represented in Figure 2-4.

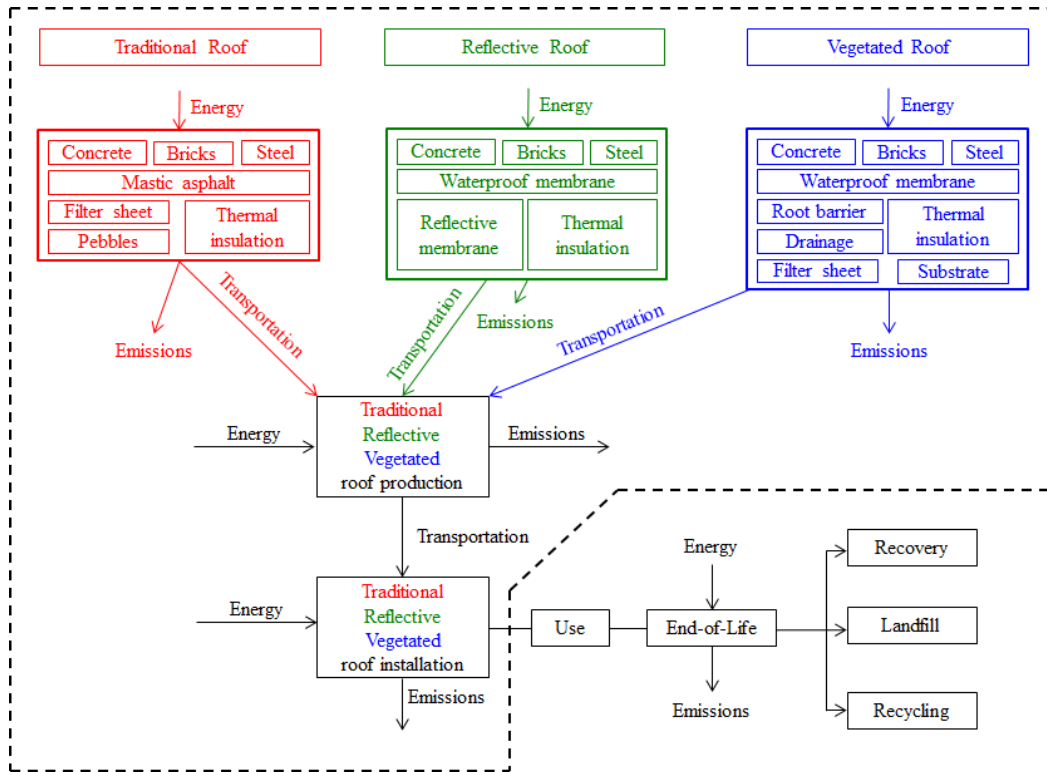


Figure 2-4: Boundaries for TGBR, WRR, and VRs

2.4.2 Life Cycle Inventory (LCI)

LCI consists of compiling the amount of construction materials, transportation type, transportation distance, and consumed energy during the assembly phase.

2.4.2.1 Background and foreground data

Data collection is one of the most time consuming activities in LCA. It could be obtained via direct measurements, collected from literature, internet, and LCI databases, or via interviews. In this respect, data are split into background and foreground data. In this study, background data are picked from SimaPro database especially the European or the world context. As for the foreground data, they were acquired by interviews, calculations, and from literature. **Table 2-1** illustrates the amount of materials used to build TGBR, WRR, EGR, and IGR for an area of 834 m², while **Table 2-2** displays transportation type and shipping distance for the different used materials. Distances were then converted to ton-kilometers (tkm) by multiplying the mass of each material by the distance travelled.

2.4.2.2 Software

LCI was modelled using SimaPro 8.0.1 software, while the IMPACT 2002+ methodology was selected as the LCIA method [3, 4]. In line with that, the Ecoinvent library (version 3.1) was utilized to choose the type of energy used to lift each component until the building rooftop [5]. Moreover, the Ecoinvent library served to state the amount of gas and electricity used to cut and install steel, waterproof, thermal insulation, and reflective layers/components.

Example of calculation:

- **Hollow concrete blocks calculation**

1. From a personal communication with the owner of a bricks factory, the recommendations for each 32 hollow concrete blocks are to be made of:

- 120 kg of crushed gravel
- 12 kg of sand
- 60 kg of limestone powder
- 18 kg of water
- 50 kg of cement

Thus each 32 hollow concrete blocks weigh 260 kg consequently one hollow concrete block weighs 8.125 kg,

2. Several contractors suggest using 8 hollow concrete blocks per 1.69 m².
3. The total quantity of hollow concrete blocks needed for 834 m² is equal to $\left(\frac{834 \times 8}{1.69}\right) = 3950$,
4. The total weight of hollow concrete blocks was equal to $\left(\frac{3950 \times 8.125}{1000}\right) = 32.09$ tons per 834 m².
5. The hollow concrete blocks were shipped by truck for a distance of 5.8 km since the factory and the installation site are both located in Hamra => tkm = ton × kilometer = 32.09 × 5.8 = 186.12.

- **Steel calculation:**

1. Local civil engineers recommend the use of 50 kg of steel per 1 m³ of concrete,
2. The average thickness of the roof assembly in Lebanon is 27 cm,

3. The total roof volume was $834 \times 0.27 = 225.45 \text{ m}^3$,
4. The total weight of steel was equal to $\frac{50 \times 225.45}{1000} = 11.27$ tons per 834 m^2 .
5. Steel was shipped by:
 - Truck from the Industry to Shanghai port-CHINA for a distance of 19.0 km =>
tkm = ton \times kilometer = $11.27 \times 19.0 = 214.1$.
 - Boat from Shanghai port-CHINA to Port of Beirut-LEBANON for a distance of 13,719.9 km => tkm = ton \times kilometer = $11.27 \times 13,719.9 = 154,623.3$.
 - Truck from Port of Beirut-LEBANON to Hamra-LEBANON for a distance of 4.5 km => tkm = ton \times kilometer = $11.27 \times 4.5 = 50.72$.

More details about the amount of materials used to build 834 m^2 of each type of roof can be found in **Appendix B**, while the detailed shipping distances, for various material types and conversion to “tkm” are listed in **Appendix C**.

Table 2-1: Amount of materials, in tons, used to build 834m² of TGBR, WRR, EGR, and IGR

Components		Specifications	SimaPro materials	TGBR	WRR	EGR	IGR
Bricks			Sand-lime brick {RoW} production Alloc Def, U	32.09	32.09	32.09	32.09
Steel	Lebanese manufacturer	Local technicians and civil engineers	Reinforcing steel {RER} production Alloc Def, U	11.27	11.27	11.27	17.51
Concrete			Concrete, {RoW} production Alloc Def, U	405.78	405.78	405.78	453.61
Mastic asphalt			Mastic asphalt {RoW} production Alloc Def, U	10.01	---	---	---
Waterproof membrane	Lebanese supplier		Polyester resin, unsaturated {RoW} production Alloc Def, U	---	3.34	3.34	4.17
Thermal insulation			Polystyrene foam slab {GLO} market for Alloc Def, U	0.96	1.25	0.96	2.41
Root barrier		UNDP, CEDRO project	Polyethylene, high density, granulate {RER} production Alloc Def, U	---	---	0.27	0.94
Drainage	German manufacturer		Polyethylene, high density, granulate {RER} production Alloc Def, U	---	---	1.67	1.92
Filter sheet			Polypropylene, granulate {RER} production Alloc Def, U	0.83	---	0.83	0.83

“- - -” : Material/component not needed for the particular roof.

Table 2-1 (continued): Amount of materials, in tons, used to build 834m² of TGBR, WRR, EGR, and IGR

Components	Specifications	SimaPro materials	TGBR	WRR	EGR	IGR
Sand		Sand {GLO} market for Alloc Def, U	- - -	- - -	110.23	801.64
Fertilizer		Nitrogen fertiliser, as N {GLO} field application of compost Alloc Def, U	- - -	- - -	0.83	1.33
Pozzolan	Lebanese supplier	UNDP, CEDRO project				
		Hard coal ash {Europe without Switzerland} cement production, pozzolana and fly ash 36-55%, non-US Alloc Def, U	- - -	- - -	47.06	322.76
Perlite		Perlite {GLO} market for Alloc Def, U	- - -	- - -	24.08	165.13
Pebbles	Lebanese manufacturer	Local technicians and civil engineers				
		Gravel, round {GLO} market for Alloc Def, U	231.81	- - -	- - -	- - -
Reflective membrane		Polyester resin, unsaturated {RoW} production Alloc Def, U	- - -	3.50	- - -	- - -

“- - - ” : Material/component not needed for the particular roof.

Table 2-2: Transportation types, shipping distances, and SimaPro Processes for the different materials used

	Type	SimaPro Process	Distance (<i>km</i>)
Bricks	Road freight	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} Alloc Def, U	5.80
	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	19.00
Steel	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	13,719.97
	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	4.50
Concrete	Road freight	Municipal waste collection service by 21 metric ton lorry {RoW} Alloc Def, U	9.00
Mastic asphalt	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	5.30
Waterproof membrane	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	604.00
	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,082.35
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	3.90
Thermal insulation	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	32.40
	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	1,668.00
	Road freight	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} Alloc Def, U	2.30
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	398.00
Root barrier	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,569.48
	Road freight	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} Alloc Def, U	3.90

Table 2-2(continued): Transportation types, shipping distances, and SimaPro Processes for the different materials used

	Type	SimaPro Process	Distance (km)
Drainage	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	398.00
	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,569.48
	Road freight	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} Alloc Def, U	3.90
Filter sheet	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	398.00
	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,569.48
	Road freight	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RoW} Alloc Def, U	3.90
Sand	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	36.00
Fertilizer	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	59.20
	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,248.21
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	3.90
Pozzolan	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	1,553.40
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	3.90
Perlite	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	1,553.40
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	3.90

Table 2-2(continued): Transportation types, shipping distances, and SimaPro Processes for the different materials used

Type		SimaPro Process	Distance (<i>km</i>)
Pebbles	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	118.00
Reflective membrane	Road freight	Transport, freight, lorry >32 metric ton, EURO4 {RER} Alloc Def, U	398.00
	Sea freight	Transport, freight, transoceanic ship {GLO} processing Alloc Def, U	6,569.48
	Road freight	Transport, freight, lorry 16-32 metric ton, EURO4 {RoW} Alloc Def, U	3.90

2.4.3 Life Cycle Impact Assessment (LCIA)

LCIA aims to translate the findings of the inventory to an impact profile. The latter consists of a set of different environmental impact categories, such as land occupation, global warming, ozone depletion, etc. (refer to section 1.2.2.3 in chapter 1). In this research, the IMPACT 2002+ methodology (incorporated into SimaPro) was selected as the LCIA method.

2.4.4 Life Cycle interpretation

To better interpret and verify the robustness of depicted results, contribution, sensitivity, and uncertainty analyses were performed. In particular, for TGBR, WRR, EGR, and IGR, the contribution of each of the components to the potential environmental impacts were studied. This helps identify the largest contributors (i.e. “hotspots”) and propose ways to lessen the environmental burden of the particular roof. Sensitivity analyses were also performed for the amounts of rebar, concrete, and fertilizer. This was done because the amounts of these materials were calculated based on assumptions made after personal communication with civil engineers, technicians and landscape experts. An uncertainty analysis was also accomplished using Monte Carlo simulation in SimaPro with a fixed number of 1,000 runs, a stop factor of 0.005, and a confidence interval of 95%. Findings are elaborated in chapter 3.

2.5 Experimental bench: different roof mockups

2.5.1 Description of the experimental bench

The experimental bench is made of a TGBR mockup and two EGR mockups. The 70x70 cm mockups were built and assembled on the rooftop of the Chemical Engineering Department at the University of Balamand, Lebanon (34°31'N, 35°50'E) in December 2015.

The TGBR mockup was made of roof assembly, a mixture of one hollow concrete block, 0.10 m³ of concrete, and 6.5 kg of rebar, waterproof membrane, thermal insulation layer, filter sheet, and a pebbles layer of 10 cm. EGRs are composed of roof assembly (same as for TGBR), waterproof membrane, thermal insulation layer, anti-root membrane, drainage layer, filter sheet, growing medium, and vegetation layer. EGRs differ by the depth and the composition of the substrate layer. The first one is a mixture of soil, peat, alumina, pumice, and fertilizer and measures 8 cm depth. Thus it is labelled “EGR8”. The second one is a mixture of soil, peat, pumice, and fertilizer and measures 16 cm depth. Thus it is labelled “EGR16”.

2.5.2 Description of the construction process

The first step in this process was the construction of roof assembly for the three mockups; a square wood mold of 27 cm height was fixed and one hollow concrete block was then set in the middle and surrounded by rebar. In parallel, concrete was well mixed and poured. Afterwards, the roof assembly was irrigated for 72 hours. Later, the wood mold was taken off and a pierced wood border of 25 cm height was fixed to the roof assembly. At this stage, the relative layers of each mockup were assembled. When all layers of EGR mockups were mounted the soil was saturated with water (irrigated until it drains) and few grams of organic fertilizer were added in order to ensure a good environment for the new plants. The composition of each roof mockup is briefly explored in **Table 2-3** and detailed in **appendix D**. **Figure 2-5** displays the TGBR, EGR8, and EGR16 mockups.

Table 2-3: Composition of TGBR, EGR8, and EGR16 mockups

	TGBR	EGR8	EGR16
	Brick: 1	Brick: 1	Brick: 1
Roof assembly	Steel: 6.61 kg	Steel: 6.61kg	Steel: 6.61kg
	Concrete: 0.10 m ³	Concrete: 0.10 m ³	Concrete: 0.10 m ³
Thermal insulation	Styrofoam	Styrofoam	Styrofoam
Waterproof	SBS waterproof	SBS waterproof	SBS waterproof
Root resistant barrier	- - -	ZinCo WSF 40	ZinCo WSF 40
Drainage	- - -	ZinCo FD 40-E	ZinCo FD 40-E
Filter	ZinCo SF	ZinCo SF	ZinCo SF
		Soil: 11.20 kg	Soil: 25.60 kg
		Peat: 21.45 kg	Peat: 41.25 kg
Growing medium	- - -	Alumina: 28.80 kg	Alumina: 0.00 kg
		Pumice: 5.13 kg	Pumice: 19.87 kg
		Fertilizer: 0.02 kg	Fertilizer: 0.04 kg

“- - -” : Material/component not needed for the particular roof mockup.

Table 2-3 (continued): Composition of TGBR, EGR8, and EGR16 mockups

	TGBR	EGR8	EGR16
Vegetation	- - -	Rosemary	Rosemary
	- - -	Lavender	Lavender
	- - -	Alyssum	Alyssum
	- - -	Argyranthemum madeira	Argyranthemum madeira
	- - -	Marguerite daisy	Marguerite daisy
	- - -	Gazania rigens	Gazania rigens
Pebbles	10 cm	- - -	- - -

“- - - ” : Material/component not needed for the particular roof mockup.

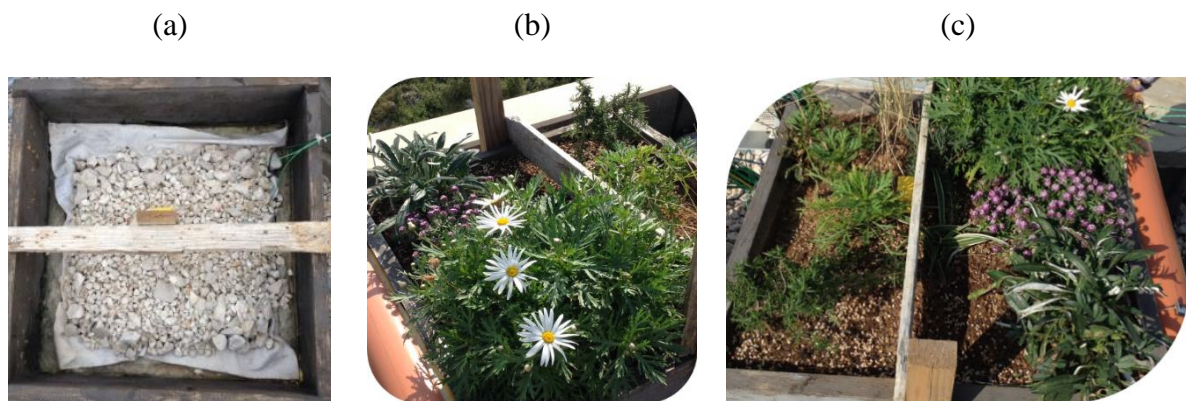


Figure 2-5: Mockups at the roof of the Chemical Engineering building: (a) TGBR (b) EGR8 (c) EGR16

2.5.3 Installation of the sensors

2.5.3.1 Installation of temperature sensors and measurements

2.5.3.1.1 Installation of thermocouples

The internal roof temperature (between layers and at different substrate depth) of the three mockups was measured using 12 thermocouples of type K from Mesurex, France and recorded with the measurement and control datalogger CR1000 connected to a channel relay multiplexer AM 16/32B produced by Campbell Scientific, U.S.A. Temperature was documented every minute starting January 14, 2016 for all mockups.

During the assembly phase (**Figure 2-6**), TGBR was equipped with two temperature probes, the first between thermal insulation layer and waterproof membrane, and the second between

filter sheet and pebbles layer. For EGR8, five thermocouples were installed, the first one between thermal insulation layer and waterproof membrane, and the others at the depth of 2, 4, 6, and 8 cm of the substrate layer. Similarly, for EGR16, five thermocouples were mounted, the first between thermal insulation layer and waterproof membrane, and the rest at 1, 6, 11, and 16 cm of the substrate depth. The schematic of temperature probes location in/above TGBR, EGR8, and EGR16 mockups is illustrated in **Figure 2-7**.

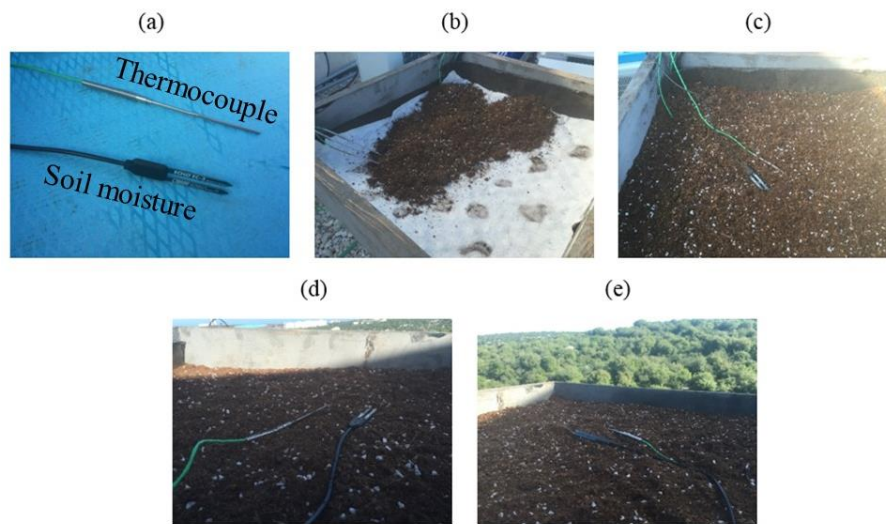


Figure 2-6: Temperature and soil moisture sensors for EGR8 and EGR16: (a) above thermal insulation board (b) at depth 1^{*,#} (c) at depth 2^{*,#} (d) at depth 3^{*,#} (e) at depth 4^{*,#}

“1^{*}=EGR8-8, 1[#]= EGR16-16, 2^{*}=EGR8-6, 2[#]=EGR16-11, 3^{*}=EGR8-4, 3[#]=EGR16-6, 4^{*}=EGR8-S, 4[#]= EGR16-S.”

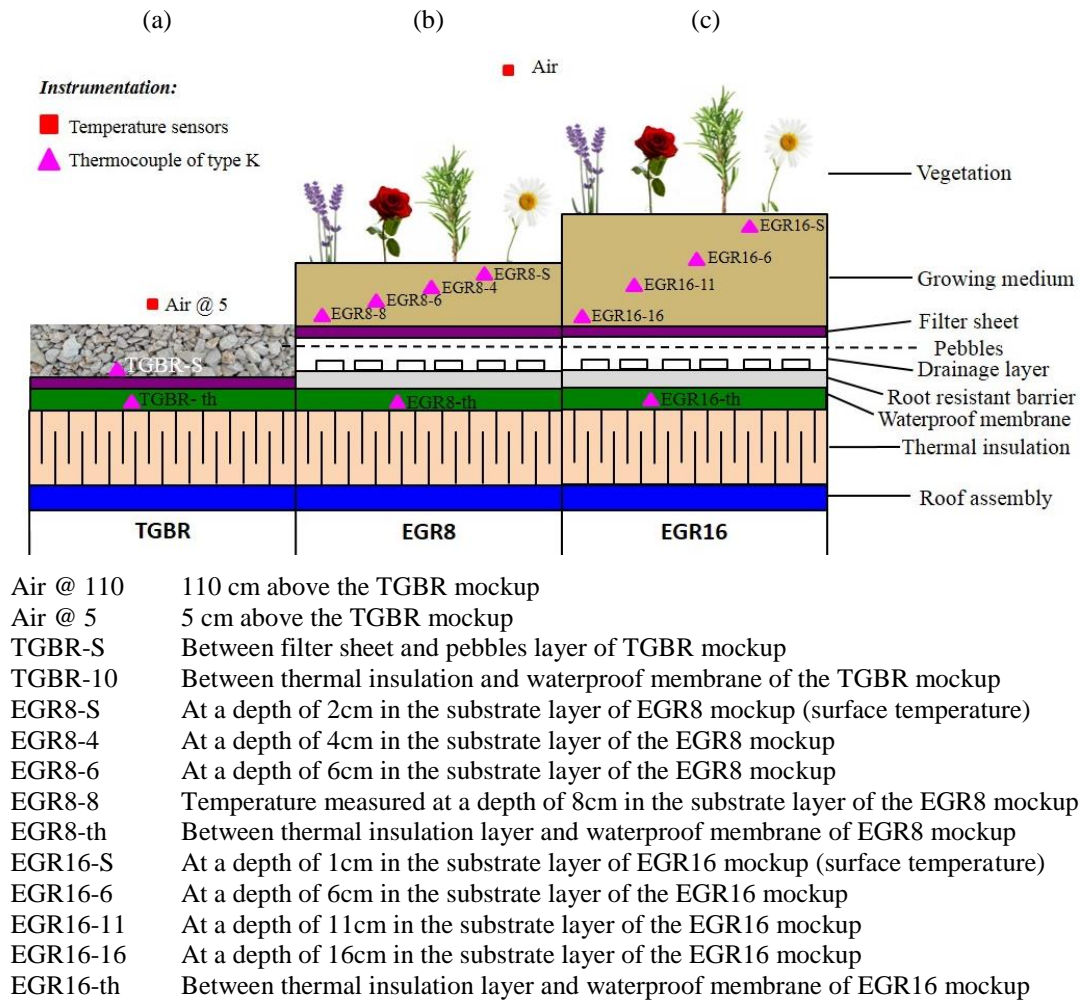


Figure 2-7: Thermocouples and temperature sensors location in/above: (a) TGBR (b) EGR8 and (c) EGR16 mockups

2.5.3.1.2 Installation of temperature sensors

Air temperature was monitored using a waterproof temperature sensors ordered from Gemini Data Loggers, United Kingdom. The temperature was recorded every minute starting January 14, 2016 with Tinytag explorer 4.9. Air temperature was measured at 5 and 110 cm above TGBR mockup (**Figure 2-8**).



Figure 2-8: Waterproof and temperature sensor at the heights of: (a) 5 cm (b) 110 cm

2.5.3.2 Installation of water sensors and measurements

2.5.3.2.1 Installation of volumetric water content sensors

The internal VWC of the roof (between layers and at different substrate depth) of the three mockups was measured using a total of 12 soil moisture sensors (ECH₂O EC-5) from Decagon devices, U.S.A. and recorded with the measurement and control datalogger CR1000 connected to a channel relay multiplexer AM 16/32B produced by Campbell Scientific, U.S.A. Temperature was documented every minute starting January 14, 2016 for all mockups (**Figure 2-6**).

Figure 2-9 depicts the location of the soil moisture probes and RH sensors in/above TGBR, EGR8, and EGR16 mockups. TGBR was mounted with two soil moisture sensors, the first between thermal insulation layer and waterproof membrane, and the second between filter sheet and pebbles layer. For EGR8, five soil moisture probes were positioned, the first between thermal insulation layer and waterproof membrane, and the others at the depth of 2, 4, 6, and 8 cm of the substrate layer. Similarly, for EGR16, five soil moisture probes were installed, the first between thermal insulation layer and waterproof membrane, and the rest at 1, 6, 11, and 16 cm of the substrate depth. The location of the soil moisture probes and the RH sensors is displayed in **Figure 2-9**.

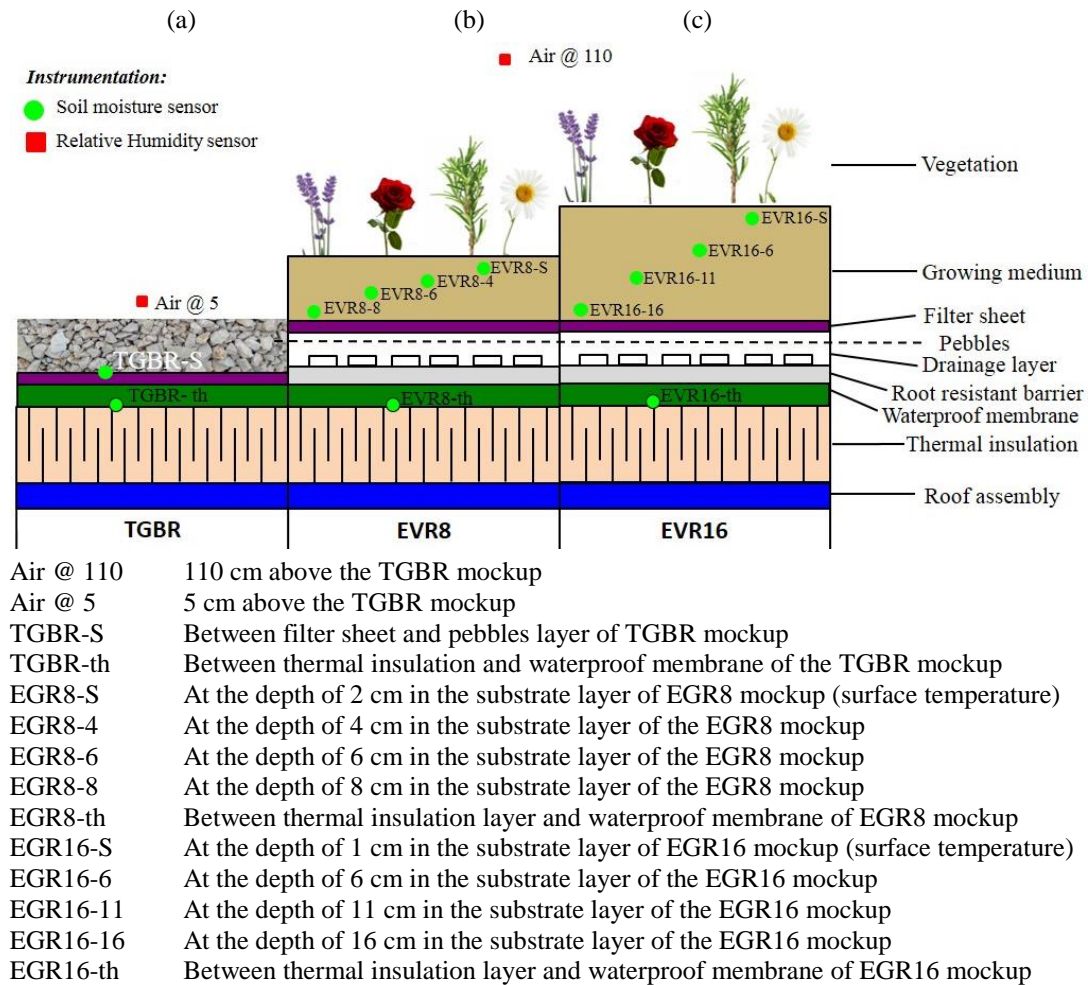


Figure 2-9: Soil moisture and relative humidity sensors location for: (a) TGBR (b) EGR8 and (c) EGR16 mockups

2.5.3.2.2 Installation of relative humidity sensors

To measure the air Relative Humidity (RH), waterproof RH sensors were ordered from Gemini Data Loggers, United Kingdom. RH was recorded every minute starting January 14, 2016 with Tinytag explorer 4.9. Waterproof RH sensors were mounted 5 and 110 cm above TGBR mockup (**Figure 2-8**).

2.5.3.2.3 Installation of rain gauges

The last step of the assembly phase was the installation of rain gauges. For TGBR mockup, the runoff water path goes to the rain gauge through the green plastic tube. As for EGR mockups, water drains in two directions either from the substrate or from the roof assembly. From the substrate, runoff water reaches the rain gauges through the orange PVC pipe mechanically fixed to the pierced wood boards. These boards were painted with mastic asphalt to minimize, as much as possible, the water absorption (**Figure 2-10.a**). In the second direction, the runoff

water reaches the rain gauges from the bottom of the roof assembly through a green plastic tube (**Figure 2-10.b**).

In fact, runoff dynamics were monitored using three rain gauges (**Figure 2-10.c**) mounted on each roof mockup. An additional rain gauge was used to quantify the amount of rainfall. Rain gauges operate with a tipping bucket mechanism and has a resolution of 0.25 mm of rain per tip. Correspondingly, runoff volume, rainfall duration, runoff time, delay between runoffs, and duration between two precipitations were calculated.

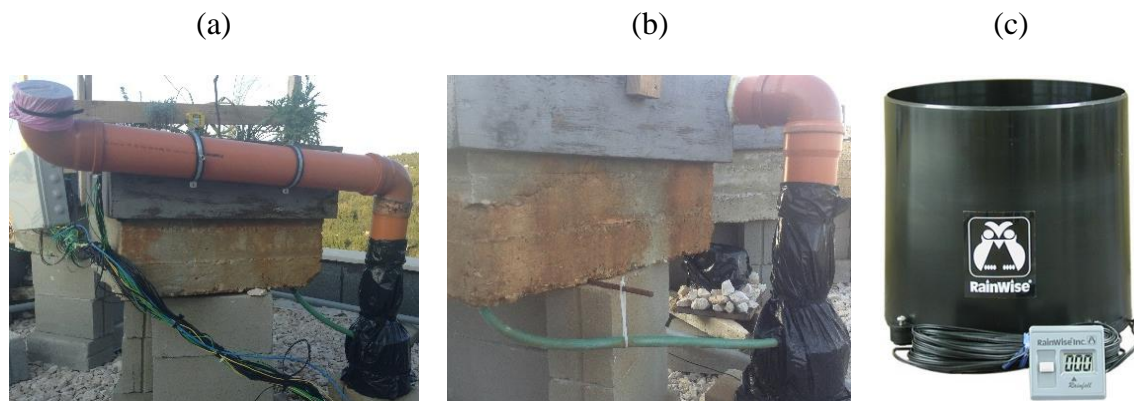


Figure 2-10: Exterior drainage system: (a) PVC pipe (b) plastic tube (c) Rain gauge

2.6 Procedure for the calculation of results

2.6.1 Thermal performance

Temperature profiles are shown in 7 sets. The first set is the daily average temperature under substrates layer, on TGBR surface, and in the air. The second set is the daily amplitude temperature under substrates layer, on TGBR, EGR8, and EGR16 surfaces, and in the air. The following set is the monthly variation of temperature amplitudes under substrates layer, on TGBR surface, and in the air. The next set is daily variation of temperature amplitudes at different EGR8 substrate depths, on TGBR surface, and in the air. Another set is the daily variation of temperature amplitudes at different EGR16 substrate depths, on TGBR surface, and in the air. The last two sets are the hourly temperature variation at different substrate depths, on TGBR surface, and in the air during a typical cold winter day and a typical sunny winter day.

2.6.2 Economic study

2.6.2.1 Heating/cooling degree day

A Degree Day (DD) is an indicator of the household heating or cooling consumption for a specific period of time. Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) were calculated using average daily temperatures according to **Equations 2-1 and 2-2** respectively. **Equations 2-3** was used to convert the HDDs and CDDs to heating and cooling costs. The complete calculation of HDD and CDD are available in **appendix E and F** respectively.

$$\text{HDD} = T_{\text{base}} - T_A \quad \text{Equation 2-1: HDD formula [6]}$$

HDD = Heating Degree Day

T_{base} = Base temperature in Celsius degree (18°C)

T_A = Average daily temperature in degree Celsius

$$\text{CDD} = T_A - T_{\text{base}} \quad \text{Equation 2-2: CDD formula [6]}$$

CDD = Cooling Degree Day

T_{base} = Base temperature in Celsius degree (21°C)

T_A = Average daily temperature in degree Celsius

$$E = DD \times F \times P \quad \text{Equation 2-3: Cost calculation using HDD or CDD}$$

E = Cost of electricity for heating or cooling (US\$)

DD = HDD or CDD

F = Occupancy effect factor (0.70)

P = Price of electricity (EDL: US\$ 0.17/kWh; PG: US\$ 0.32/kWh)

2.6.2.2 Construction cost of 1m² of TGBR, EGR8, and EGR16

The construction cost of 1m² of TGBR, EGR8, and EGR16 is divided into two phases. The first one, is the calculation of the amount of each component or material needed to build 1m² of each roof mockup. The second phase, lies in estimating the cost of each layer. Together, these two phases leads to the total construction cost of 1m² of each roof mockup.

2.6.2.3 Money saving

The economic study for TGBR, EGR8, and EGR16 was performed and evaluated following the schematic represented in **Figure 2-11**.

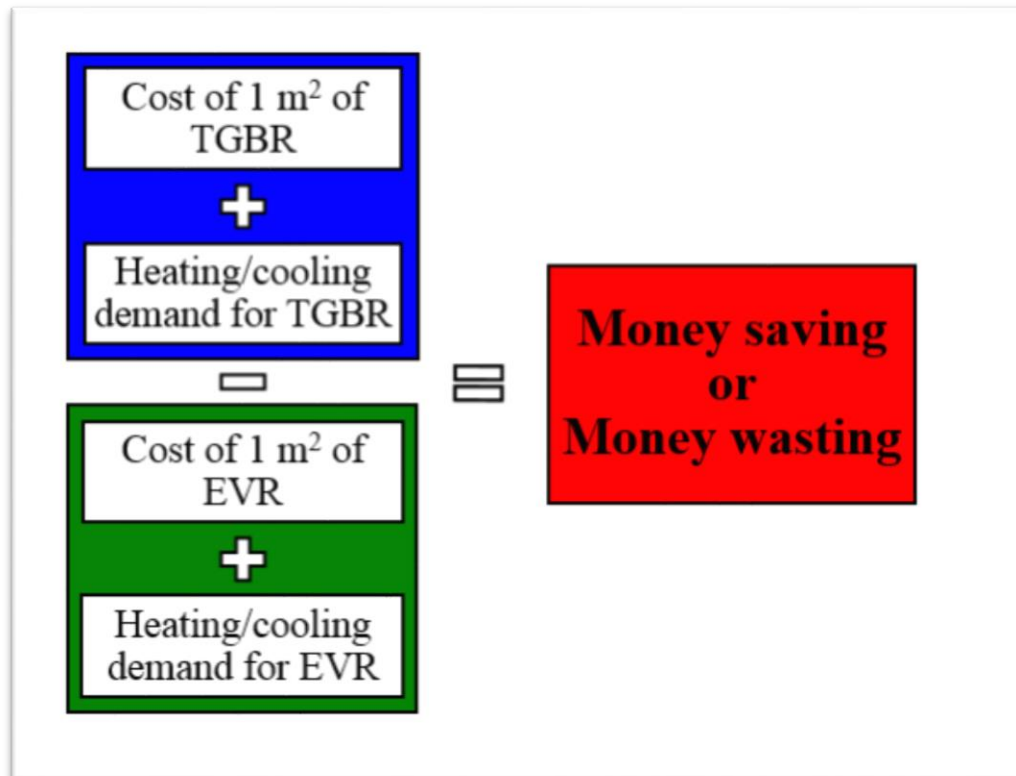


Figure 2-11: Schematic of the economic study

2.6.3 Water performance and runoff dynamics

2.6.3.1 Runoff water quantity

Rain gauges measure the amount of rainfall water as well as the amount of runoff water from each roof mockup. When doing the math, one can conclude the volume of water that is retained by each roof mockup.

2.6.3.2 Runoff water quality

After each rainfall, 250 mL of rain water and runoff water from TGBR, EGR8, and EGR16 were collected in glass bottles with polyethylene cover. Prior to sampling, glass bottles were rinsed multiple times with demineralized water. For best results, samples were analyzed immediately using chemical color comparator tests in the Chemical Engineering Laboratories at the University of Balamand.

2.6.3.2.1 Chemical tests

2.6.3.2.1.1 pH test

The pH measures concentration of the hydrogen ions indicating the acidity or alkalinity of the water on a scale of 1 to 14. The pH values were obtained by a benchtop meter (pH meter inoLab pH 7110) ordered from WTW GmbH (**Figure 2-12**).



Figure 2-12: Benchtop Meter

Before and after each measurement, the pH electrode was rinsed with demineralized water then immersed in the test sample. Afterwards, the pH and the temperature records were displayed.

2.6.3.2.1.2 Nutriments and heavy metals tests

The loads of nutriments (Ca^{2+} and NH_4^+) and heavy metals (Cd, Cu, Cr, Fe, and Zn) in rain water and runoff water from TGBR, EGR8, and EGR16 was quantified using color comparator tests (AQUANAL-plus) ordered from Sigma-Aldrich and summed up in **Table 2-4**.

For all tested elements except for the total hardness test, a certain volume of water sample was poured to a glass tube, then the needed reagents were added, dissolved by shaking, and left to stand for few minutes. The last step is the color comparison between the test tube and the color comparator chart. As for the total hardness test, a certain volume of water sample and the first reagent were added to a glass tube. Next, the tube is slightly shaken. Then, the second reagent is added, drop by drop, until the conversion of colors from red to green.

Table 2-4: Color comparator tests [7]

	Measuring range	Method
Cadmium	0.02-1.25mg/L Cd	Formation of a yellow- red color complex
Copper	0.05-0.5mg/L Cu ²⁺	Formation of a blue color complex
	0.4-4.5mg/L Cu ²⁺	
Iron	0.2-15mg/L Fe ^{2+/3+}	Formation of a red color complex
Chromium	0.005-0.1 mg/L Cr ²⁺	Formation of a red-violet dye
Zinc	0.1-5mg/L Zn ²⁺	Formation of a green color complex
Ammonium	0.2-8mg/L NH ₄ ⁺	Formation of blue color
Total-hardness	0.178mmol/L Ca	Variation of color from red to green

2.7 References

- [1] Kosareo L, Ries R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and Environment* 42, 2606–2613
- [2] Educational Community for Homeowners. (2016). Guide to solar-reflective paints for energy-efficient homes. Retrieved from <http://www.echo-ca.org/article/guide-solar-reflective-paints-energy-efficient-homes>. Accessed on June 17, 2016
- [3] Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E. (2013). Introduction to LCA with SimaPro. <http://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf>. Accessed on July 20, 2015
- [4] Jolliet O, Margni M, Charles R, Humbert S, Jérôme P, Rebitzer G, and Rosenbaum R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *Int J LCA* 8(6): 324-330
- [5] Ecoinvent. (2015). <http://www.ecoinvent.org/>. Accessed on June 17, 2016
- [6] Hao, Y., Chen, H., Wei, Y., & Li, Y. The influence of climate change on CO₂ (carbon dioxide) emissions: An empirical estimation based on Chinese provincial panel data. *Journal of Cleaner Production*, doi: <http://dx.doi.org/10.1016/j.jclepro.2016.04.117>
- [7] <http://www.sigmaaldrich.com/catalog/search?term=AQUANAL%E2%84%A2-plus&interface=All&N=0&mode=match%20partialmax&lang=en®ion=LB&focus=product>

CHAPTER 3 CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF TRADITIONAL GRAVEL BALLASTED, WHITE REFLECTIVE, AND VEGETATIVE ROOFS: A LEBANESE CASE STUDY

3.1 Abstract

Lebanon, a Mediterranean country, lacks a clear sustainability plan as well as an infrastructure update and management, leading to road flooding, especially in urban areas. Therefore, the installation of Vegetative Roofs (VRs) could be an interesting option for Lebanon. To evaluate if VRs are truly superior to Traditional Gravel Ballasted Roofs (TGBRs) and White Reflective Roofs (WRRs), a cradle-to-gate Life Cycle Assessment (LCA) was performed. Potential environmental impacts of an existing Extensive Green Roof (EGR) were compared to three fictitious roofs of the same area: TGBR, WRR, and Intensive Green Roof (IGR). The functional unit used for comparison was: “providing a cover for a surface area of 834 sqm and for 45 years”. Specifications of TGBRs and WRRs were provided by local technicians and civil engineers. Furthermore, specifications of VRs were provided by the United Nations Development Program (UNDP), Country Energy Efficiency and Renewable Energy Demonstration for the recovery of Lebanon (CEDRO) project. The SimaPro software and Ecoinvent library were used to model the systems considered. Results clearly indicated that EGR was the best option for all environmental impact categories. Rebar, concrete, and thermal insulation were the main contributors to the environmental impacts for TGBR, while rebar, concrete, thermal insulation, and waterproof membrane were the highest contributors for WRR. Sensitivity and uncertainty analysis were also performed to verify the robustness of the results.

3.2 Introduction

Vegetative Roofs (VRs), also termed as garden roofs, are "roof systems that promote the growth of plants on rooftops" [1]. In addition to embellishing the roof surface, VRs offer many advantages. They protect the roof assembly from solar radiation and hail damages, hence lowering its temperature and reducing temperature fluctuations in spaces underneath it ranging from 1 to 3 floors [2]. Another advantage of VRs is the reduction of the building energy consumption through direct shading of the roof, evapotranspiration, and improved insulation values [3, 4]. If installed on broad surfaces, VRs might also attenuate the urban heat island

effect [5], which would decrease the energy consumption in urban areas [2]. From a water management perspective, VRs capture a fraction of the rainwater through their growing medium in order to be used by the plants and then returned to the atmosphere through the evapotranspiration process [6]. Therefore, these types of roofs can reduce water runoff and help manage flooding during heavy rain in urban areas [7, 8]. Many studies showed the influence of VRs on stormwater retention in different regions in the world [9-13]. Furthermore, the vegetation layer could remove airborne pollutants picked up by rain, thus improving the quality of the runoff [14, 15].

The installation of VRs in Lebanon, a country in the Middle East, could be an interesting option, as the country lacks a clear sustainability plan as well as an infrastructure update and management, leading to road flooding in urban areas, amongst other things such as the electricity deficit and continuous need for heating/cooling systems [16-18].

In addition, the installation of VRs could help manage flooding, which is also a major problem in Lebanon. The increase in concrete and asphalt surfaces, especially in urban areas, prevents the storm water absorption, which leads to roads flooding. This water picks up pollutants such as oil, heavy metals, and animal waste, and transports them to the underground water [19, 20]. VRs could help overcome this issue since the growing medium, vegetation, and drainage layer trap and store precipitation. In particular, the water can be used by the plants during drought periods or can undergo evapotranspiration. Also, the trapping process takes some time, which delays the drainage of rainwater compared to traditional roofs or any other impermeable surface [21].

So far, only a total of five Green Roofs (GRs) have been installed in Lebanon. The one occupying the largest surface area is an Extensive Green Roof (EGR) installed at the Central Bank of Lebanon (834m²). To determine if VRs are effectively superior to Traditional Gravel Ballasted Roofs (TGBRs) and White Reflective Roofs (WRRs) for Lebanon from an environmental perspective, the Life Cycle Assessment (LCA) methodology is selected. Based on the International Organization of Standardization (ISO 14040:44) LCA is an international comprehensive and analytical tool used by governments, suppliers, manufacturers, and customers. It evaluates the potential environmental impacts of a product, service or process throughout its life cycle [22-24]. Based on science direct's database, 139 international studies were done on the LCA of VRs [25-27]. However, since climatic conditions and electric grid mix are region sensitive parameters, LCA results might be affected. Kosareo and Ries (2007) compared the LCA of EGR and IGR to TGBR in Pittsburgh, PA, USA. They found that VRs

were the best environmental option because they increase the life time of the roof assembly and reduce the energy demand [28]. Saiz *et al.* (2006) compared the LCA of TGBR, WRR, and VR located in downtown Madrid, Spain. VRs were characterized by their low solar absorbance, which decreased the temperature of the surface, therefore reducing the heat flux through the roof. With VRs, the environmental impacts were reduced by a factor ranging between 1.0 and 5.3%. Saiz *et al.* (2006) showed that with WRR, the decrease in cooling energy was 65% of that with VR [29].

In Lebanon, LCA is still a new field, only few LCA studies have been performed to date [30-32]. In particular, only three LCA studies were published which aimed to study the environmental impacts of the current Lebanese electricity system, and to compare the impacts of different solar water heaters and photovoltaic cells.

This paper aims to analyze and compare the cradle-to-gate environmental impacts of the existing 834 sqm EGR at the Lebanese Central Bank with three fictitious roofs of the same area: TGBR, WRR, and IGR. Such a comparison has never been made before for the Lebanese context.

3.3 Methods

3.3.1 Goal and scope

The goal of this research is to analyze and compare the potential environmental impacts of TGBR, WRR, EGR, and IGR. The function is “to cover a certain surface area for a period of time” and the functional unit used for the comparison is as follows: “The construction and installation of a roofing system to cover a surface of 834m² for 45 years”.

A cradle-to-gate [33] study was performed, where inputs and outputs from raw materials extraction to the assembly and installation of the roof were considered. Despite the fact that the thermal insulation of the roof affects the building energy consumption, the use and end-of-life phases were excluded from the scope of the study since these thermal properties were not experimentally explored for all the types of the studied roofs, data or proxy data for Lebanon are not publicly available online to date (there are no preceding LCA studies for the Lebanese VRs), the thermal insulation properties are highly variable from a geographical zone to another, and assumptions could lead to higher uncertainty, hence providing no added value when extrapolating results. **Figure 3-1** explores the boundaries of the systems selected.

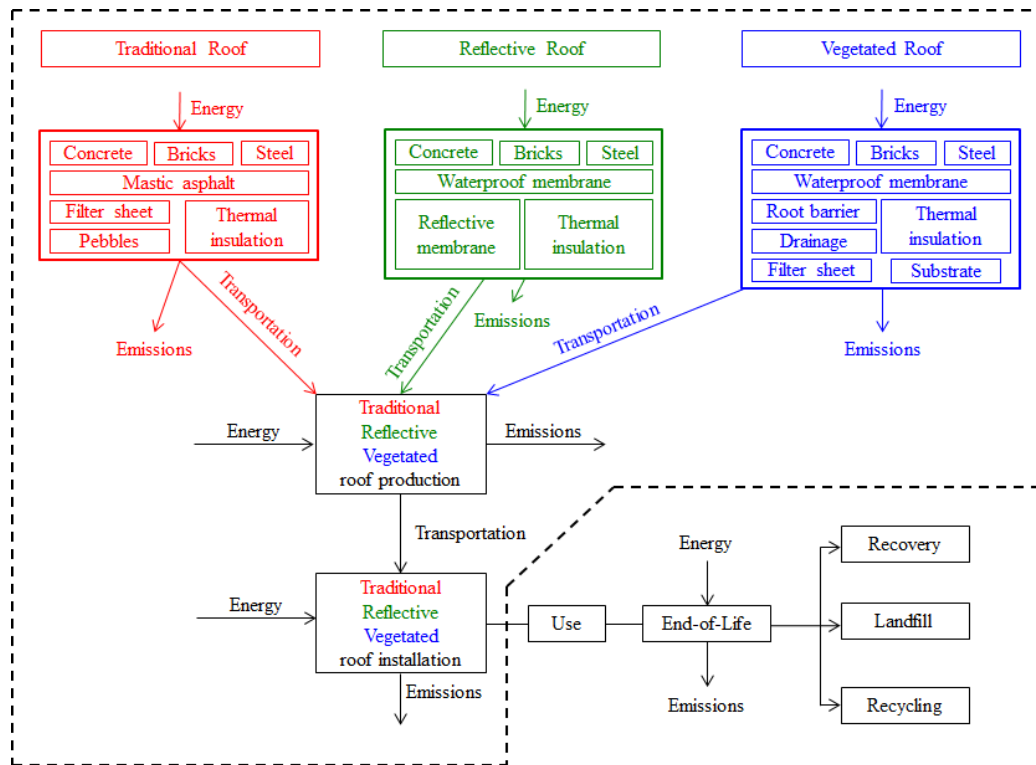


Figure 3-1: Boundaries for TGBR, WRR, EGR, and IGR

The average lifetime of the membrane of a traditional roofing system is 10–15 years before requiring replacement [28]. In this study, the life expectancy of TGBR was assumed to be 15 years. For the membrane of a reflective roofing systems, life expectancy was set 30 years [34]. As for green roofing systems, the substrate could protect the roof membrane up to 50 years. Thus the life span of VRs was assumed to be 45 years [28]. Therefore, in order to fulfill the functional unit, the reference flow was 3 for TGBR, 1.5 for WRR, and 1 for VRs.

3.3.2 Life Cycle Inventory (LCI)

TGBR consists of roofing assembly, waterproof membrane, thermal insulation layer, filter sheet, and an exterior layer made of pebbles. Roofing assembly, a mixture of hollow concrete block, rebar, and concrete, can support the weight of the intended installation, in terms of absorption of rain water or when snow melts [35]. Waterproof layers, made of mastic asphalt, help the roof to better withstand damages from wind, storms, snow, and sun. Thermal insulation boards protect the concrete from sunrays and temperature fluctuations during and between different seasons. Filter sheets prevent dusts and solid particles from circulating in water and blocking the drainage system. WRR includes some additional layers compared to TGBR. Filter and the rock layers are replaced by a white reflective membrane that reflects sunrays, reducing

the roofing system's temperature, and hence increasing its life expectancy. The different layers of VRs, from the bottom to the top, are as follows: roofing assembly, waterproof membrane, thermal insulation layer, root resistant barrier, drainage layer, filter sheet, substrate and vegetation layers [36]. The roofing assembly corresponds to the same structure of that of TGBR and WRR. Waterproof membrane is the first layer to be installed above the roofing assembly and protects the roof from water infiltration [37]. Waterproof membrane is followed by a root resistant barrier; this layer increases the lifetime of the roofing assembly by protecting it against root penetration and mechanical damage [38]. Thermal insulation layer avoids thermal losses between the interior and the exterior of the building. Drainage system is most often located on top of the thermal insulation layer in order to allow the drainage of excess water and/or to store water for the plants especially in drought periods [35]. Filter sheets separate the growing medium from the drainage layer; they are permeable to water, which provide a moist environment for plant roots and prevent the fine particles constituting the substrate of getting entrained to the drainage layer through rainwater [39]. As for the substrate, it is a mixture of soil, minerals, or high quality compost elements and aggregates (pozzolan, perlite, etc.) [40]. Vegetation could be pre-cultivated elements, plug plants, or pre-grown vegetation mats.

VRs exist in two types: extensive and intensive [41]. Mainly, they differ in the depth of the growing medium, type of vegetation, and saturated weight. The saturated weight stands for the weight of the substrate full of rain or irrigation water. In particular, the growing medium of an EGR is a thin layer (ranging between 50 and 150 mm), compared to a thick layer for IGR (ranging between 150 and 1200 mm) [28]. The second difference lies in the type of vegetation; because of its shallow depth, an EGR only sustains small plants highly resistant to cold weather such as grasses, succulents, herbs, mosses, and drought tolerant such as sedum. However, for IGR, vegetation could vary from simple turf to trees. Therefore, a low level of maintenance is required for EGR. The third difference lies in the saturated weight, which is 70-170 kg/m² for EGR, compared to 270-970 kg/m² for IGR [42, 43].

The Life Cycle Inventory (LCI) consists of compiling the amount of the different construction materials, transportation type and distance, and energy processes needed to build each of the four roofing systems. **Figures 3-2(a) to 2(c)** explore the components of TGBR, WRR, and VRs, respectively. **Figure 3-2(d)** shows the existing EGR at the headquarters of the Central Bank of Lebanon.

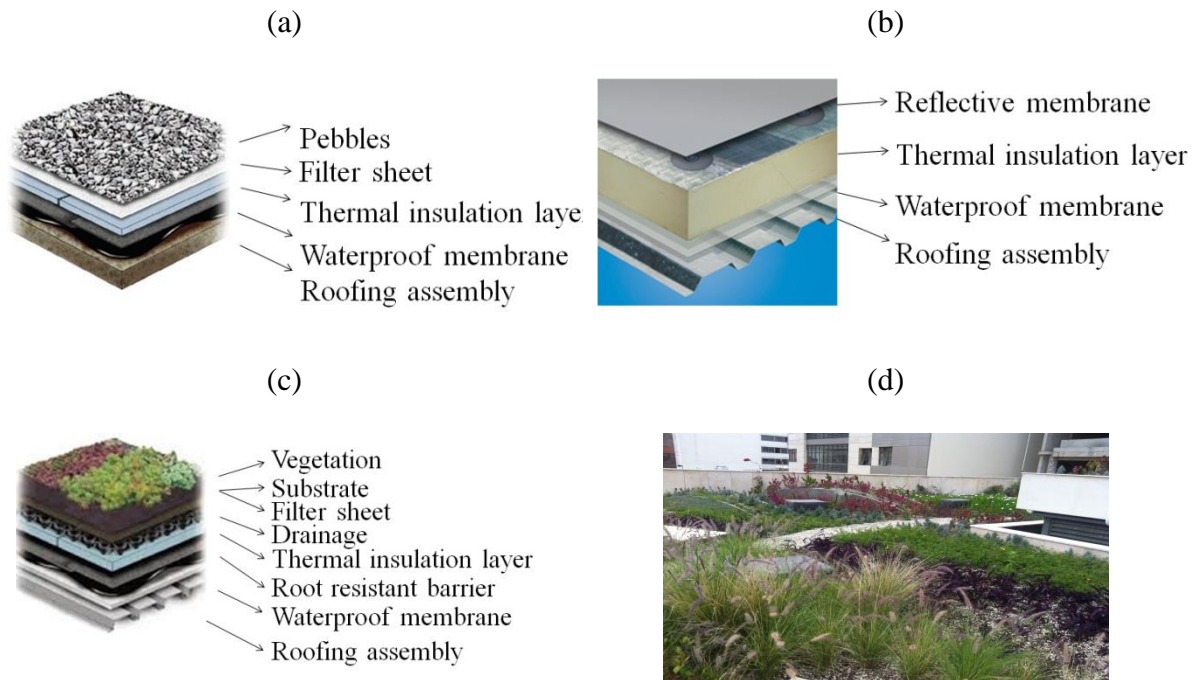


Figure 3-2: (a) TGBR (b) WRR (c) VR (d) EGR at Central Bank of Lebanon, Hamra
(Latitude 33° 19' 27.3792" N & Longitude 35° 29' 38.9760" E)

The components of VRs were supplied from a German manufacturer and their specifications were provided by the United Nations Development Program (UNDP), Country Energy Efficiency and Renewable Energy Demonstration for the recovery of Lebanon (CEDRO) project [44]. The components of TGBR and WRR were purchased from Lebanese and German manufacturers. Their respective specifications were provided by local technicians and civil engineers [45]. The substrate of EGR and IGR are, respectively, 150.0 and 1,200.0 mm in depth. Both of them consist of sand (55.0 %), pozzolan (17.5 %), perlite (17.5 %), and an organic fertilizer (10.0 %). **Table 3-1** shows the amounts of materials used to build the different roofing systems, while **Table 3-2** indicates the transportation types and shipping distances for the different types of materials. Distances were then converted to ton.kilometer (tkm) by multiplying the mass of each material by the distance travelled.

The Life Cycle Inventory was modelled using the Ecoinvent library, version 3.1 [46].

Table 3-1: Amounts of materials used to build 834m² of TGBR, WRR, EGR, and IGR in tons

	TGBR	WRR	EGR	IGR
Hollow concrete Block	32.090	32.090	32.090	32.090
Rebar	11.259	11.259	11.259	15.763
Concrete	405.745	405.745	405.745	405.745
Mastic asphalt	10.008	---	---	---
Waterproof membrane	---	4.170	4.170	4.170
Thermal insulation	2.412	2.412	2.412	2.412
Root barrier	---	---	0.275	0.942
Drainage	---	---	1.668	1.918
Filter sheet	0.834	---	0.834	0.834
Sand	---	---	110.230	801.641
Fertilizer	---	---	0.834	1.334
Pozzolan	---	---	47.064	322.758
Perlite	---	---	24.079	165.132
Pebbles	231.810	---	---	---
Reflective membrane	---	3.503	---	---

“ - - - ” : Material/component not needed for the particular roof.

Table 3-2: Transportation types and shipping distances for the different materials considered

		Type	From	To	Distance (km)
	Bricks	Road freight	Hamra, Lebanon	Hamra, Lebanon	5.800
		Road freight	Industry	Shanghai port, China	19.00
Roofing assembly	Rebar	Transoceanic freight	Shanghai port, China	Port of Beirut, Lebanon	13,719.97
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
	Concrete	Road freight	Zalka, Lebanon	Hamra, Lebanon	9.00
	Mastic asphalt	Road freight	Karantina, Lebanon	Hamra, Lebanon	5.30
Waterproof membrane		Road freight	Strasbourg, France	Port of Dunkerque, France	604.00
	SBS membrane	Transoceanic freight	Port of Dunkerque, France	Port of Beirut, Lebanon	6,082.35
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90

Table 3-2 (continued): Transportation types and shipping distances for the different materials considered

		Type	From	To	Distance (km)
Thermal insulation	Thermal insulation	Road freight	Sabhan industrial area, Kuwait	Kuwait borders	32.40
		Road freight	Kuwait borders	Beirut, Lebanon	1,668.00
		Road freight	Beirut, Lebanon	Hamra, Lebanon	2.30
	Rockwool	Road freight	Mazraet Yachouh, Lebanon	Hamra, Lebanon	18.8
		Road freight	Lise-Meitner-Straße 2, Nürtingen	Port of Cologne, Germany	398.00
	Root barrier	Transoceanic freight	Port of Cologne, Germany	Port of Beirut, Lebanon	6,569.48
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
		Road freight	Lise-Meitner-Straße 2, Nürtingen	Port of Cologne, Germany	398.00
	Drainage	Transoceanic freight	Port of Cologne, Germany	Port of Beirut, Lebanon	6,569.48
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
		Road freight	Lise-Meitner-Straße 2, Nürtingen	Port of Cologne, Germany	398.00
	Filter sheet	Transoceanic freight	Port of Cologne, Germany	Port of Beirut, Lebanon	6,569.48
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90

Table 3-2 (continued): Transportation types and shipping distances for the different materials considered

	Type	From	To	Distance (km)	
Substrate	Sand	Road freight	Daher El Baidar, Lebanon	Hamra, Lebanon	36.00
	Fertilizer	Road freight	Ghent, Belgium	Port of Antwerp, Belgium	59.20
		Transoceanic freight	Port of Antwerp, Belgium	Port of Beirut, Lebanon	6,248.21
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
		Transoceanic freight	Istanbul terminal, Turkey	Port of Beirut, Lebanon	1,553.40
	Pozzolan	Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
	Perlite	Transoceanic freight	Istanbul terminal, Turkey	Port of Beirut, Lebanon	1,553.40
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90
	Pebbles	Road freight	Akkar, Lebanon	Hamra, Lebanon	118.00
	Reflective membrane	Road freight	Lise-Meitner-Straße 2, Nürtingen	Port of Cologne, Germany	398.00
		Transoceanic freight	Port of Cologne, Germany	Port of Beirut, Lebanon	6,569.48
		Road freight	Port of Beirut, Lebanon	Hamra, Lebanon	3.90

3.3.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) aims to translate the findings of the inventory to an impact profile. The latter consists of a set of different environmental impact categories, such as land occupation, global warming, ozone depletion, etc. In this research, the inventory was modeled using the SimaPro 8.0.1 software, while the IMPACT 2002+ methodology was selected as the LCIA method [47, 48].

3.4 Results and discussion

3.4.1 Contribution of the roofs components and processes to environmental impacts

Potential environmental impacts were calculated for TGBR, WRR, EGR, and IGR. **Figures 3-3(a) to 3-3(d)** show the contribution of the components of each of the four types of roofing assemblies to the environmental impacts.

Results indicated that for TGBR (**Figure 3-3(a)**), rebar, concrete, and pebbles were the highest contributors to most environmental impacts. Rebar mostly contributed to mineral extraction, while concrete mostly contributed to global warming and ionizing radiation. Mastic asphalt was the highest contributor to ozone layer depletion, while thermal insulation boards were the major contributors to the respiratory organics and non-renewable energy impact categories. In particular, the conversion process of unalloyed to rebar causes the high contribution of rebar. This emits potentially carcinogenic aromatic hydrocarbons to air and requires cinnabar (HgS) from the ground. Because of its mercury content, cinnabar is classified as toxic to human beings. As for the concrete, the contribution was due to the emission of carbon fossil and Radon-222 to air. The mastic asphalt highly contributed to the ozone layer depletion impact category because of the emission of cryofluorane, also known as CFC-114, to air. The contribution of the thermal insulation boards is due to the polystyrene. The foaming process requires crude oil from the ground and emits pentane to the atmosphere. For the pebbles, they highly contribute to terrestrial ecotoxicity and land occupation because of the transportation process and the gravel, respectively.

With respect to WRR (**Figure 3-3(b)**), rebar, concrete, and thermal insulation barrier contributed to the same environmental impacts for the same reasons mentioned above. In addition, the white reflective membrane contributed to the depletion of the ozone layer and to

the aquatic eutrophication impact categories while the waterproof barrier contributed to the ozone layer depletion impact category. In particular, the contribution of the waterproof membrane is due to the propane/butane at the refinery emitting bromochlorodifluoromethane or Halon 1211 to the atmosphere, which causes ozone layer depletion. As for white reflective membrane, the unsaturated polyester resin increases the amount of organic pollutants on the water surface, which can cause eutrophication, as well as the emission of chlorofluorocarbon (CFC-10) to air that contribute to the depletion of the ozone layer.

For the EGR (**Figure 3-3(c)**), rebar, concrete, waterproof membrane, and thermal insulation boards were the ones contributing the most to the environmental impacts, for the same reasons previously discussed. However, for IGR (**Figure 3-3(d)**), the main contributors were the same as for the EGR, in addition to the perlite, which was a major contributor to the land occupation and to the aquatic ecotoxicity impact categories. This is because, to obtain perlite, an extraction process is required. The latter substitutes the vegetation by an industrial area and emits aluminum to the atmosphere.

Of the very few LCA studies of VRs' layers, Bozorg Chenani *et al.* (2015) found, that rock wool, plastic drainage layer, and expanded clay had the greatest environmental impacts [25]. However, in this study, the main contributors for VRs were rebar, concrete, waterproof membrane, and thermal insulation layer.

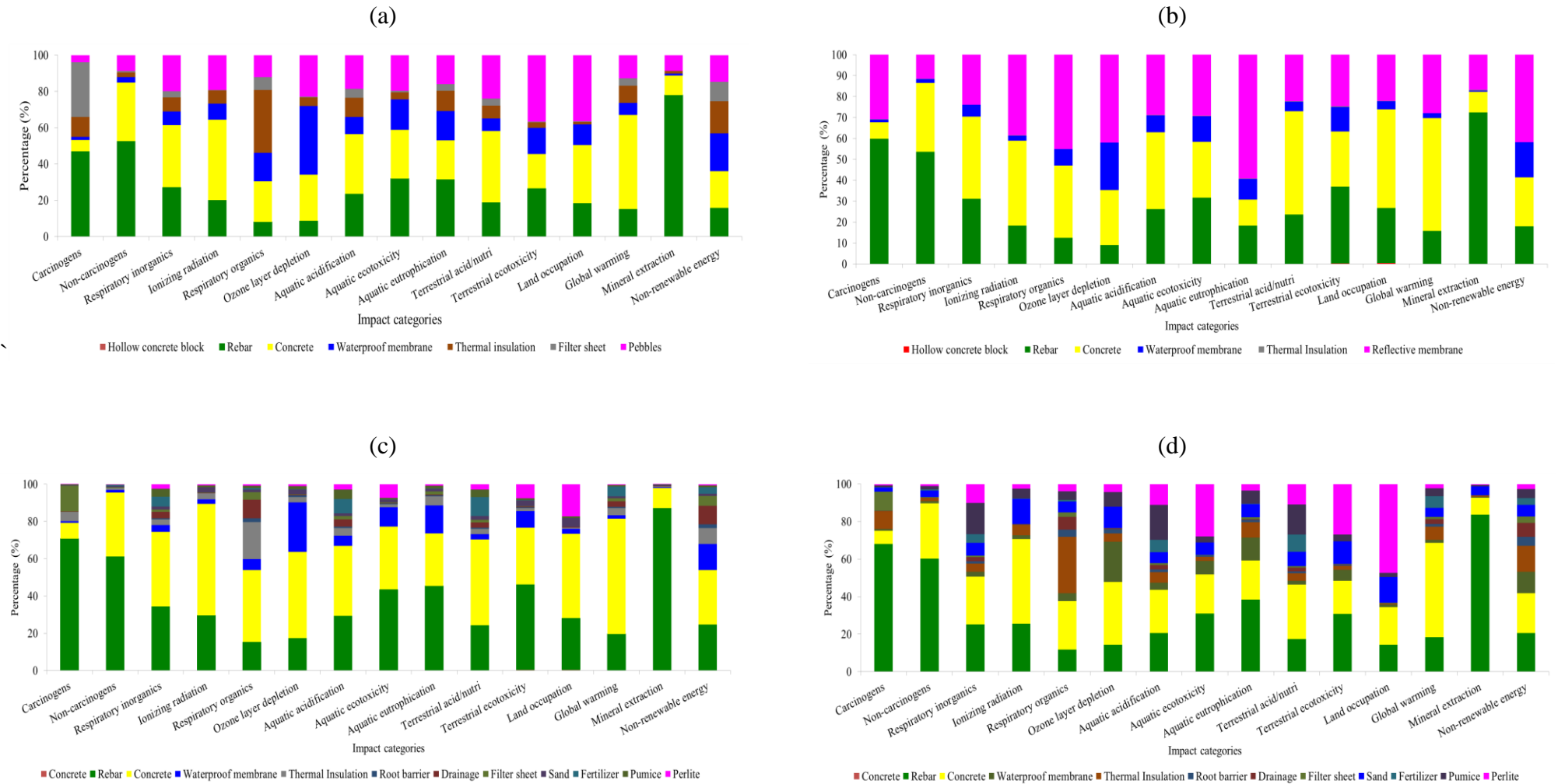


Figure 3-3: Contribution of the different components of the roofing assemblies to the potential environmental impacts for (a) TGBR (b) WRR (c) EGR (d) IGR

3.4.2 Comparative cradle-to-gate assessment

Figure 3-4 compares the environmental impacts of the existing EGR to the three fictitious roofs: TGBR, WRR, and IGR. **Table 3-3** shows the environmental impact results for each impact category and for each type of roof.

Results indicated that the IGR had the highest environmental impacts for carcinogens, ionizing radiation, ozone layer depletion, aquatic eutrophication, global warming, and non-renewable energy impact categories. For instance, the global warming potential for IGR was higher than for other roofs because of the higher amount of concrete used. WRR was the least favorable options when looking at the rest of the impact categories. Results clearly showed that EGR was the best option from an environmental perspective. For instance, EGR contributed 53% less than TGBR for the respiratory organics impact category.

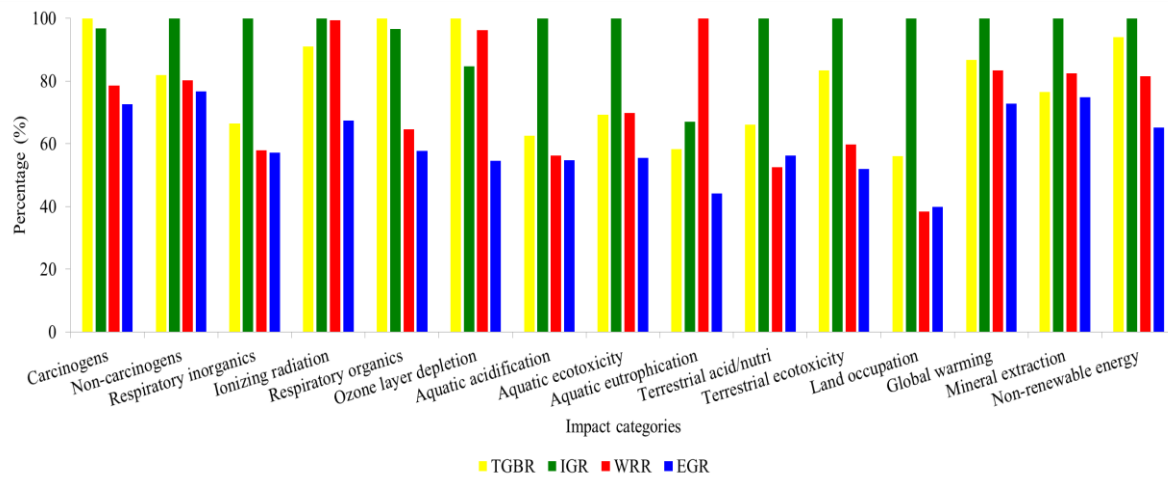


Figure 3-4: Comparative life cycle impact assessment of TGBR, WRR, EGR, and IVR.

Table 3-3: Potential environmental impacts of TGBR, WRR, EGR, and IVR

	Impact category	Unit	TGBR	WRR	IGR	EGR
	Carcinogens	kg C ₂ H ₃ Cl eq	2.9E+03	2.3E+03	2.8E+03	2.1E+03
	Non-carcinogens	kg C ₂ H ₃ Cl eq	1.9E+03	1.9E+03	2.3E+03	1.8E+03
Human health	Respiratory inorganics	kg PM _{2.5} eq	7.9E+01	6.8E+01	1.2E+02	6.8E+01
	Ionizing radiation	Bq C-14 eq	1.5E+06	1.6E+06	1.6E+06	1.1E+06
	Respiratory organics	kg C ₂ H ₄ eq	8.0E+01	5.1E+01	7.7E+01	4.6E+01
	Ozone layer depletion	kg CFC-11 eq	1.0E-02	9.8E-03	8.6E-03	5.6E-03
	Aquatic acidification	kg SO ₂ eq	4.1E+02	3.7E+02	6.5E+02	3.6E+02
	Aquatic ecotoxicity	kg TEG water	5.4E+06	5.5E+06	7.8E+06	4.3E+06
Ecosystem quality	Aquatic eutrophication	kg PO ₄ P-lim	1.1E+01	1.8E+01	1.2E+01	8.1E+00
	Terrestrial acid/nutri	kg SO ₂ eq	2.0E+03	1.6E+03	3.0E+03	1.7E+03
	Terrestrial ecotoxicity	kg TEG soil	1.8E+06	1.3E+06	2.1E+06	1.1E+06
Climate change	Land occupation	m ² org.arable	5.8E+02	4.0E+02	1.0E+03	4.1E+02
	Global warming	kg CO ₂ eq	1.2E+05	1.1E+05	1.3E+05	9.8E+04
Resources	Mineral extraction	MJ surplus	2.3E+03	2.5E+03	3.1E+03	2.3E+03
	Non-renewable energy	MJ primary	1.8E+06	1.6E+06	1.9E+06	1.2E+06

Results were in agreement with those of Lamnatou and Chemisana (2015). They found that the PV-green roofs (PV panels over a soil/plant layer) were eco-friendlier than the PV-bitumen and the PV-gravel systems [49].

Also, the cradle-to-grave study done by Kosareo and Ries (2007) also found that VRs were an environmentally desirable option compared to conventional roof due to the reduction in energy demand and the increased lifetime of the roof membrane [28].

3.4.3 Sensitivity analysis

A sensitivity analysis is defined as a “Procedure to identify which assumptions (modelling of the product system, scope definition, unit processes and data selected...) are of greatest significance for the result of the LCA” [50]. A sensitivity analysis was done for the amounts of rebar, concrete, and fertilizer; because the amounts of these materials were calculated based on assumptions made after personal communication with civil engineers, technicians and landscape experts [45, 51]. Results depicted that the environmental impacts were not significantly affected by the variation in amounts of concrete and fertilizer. In contrast, the environmental impacts were influenced by the fluctuation of the amount of rebar (**Figure 3-5**). Most of the civil engineers recommend 11.259 tons per 834m², while some recommended using 15.763 or 20.266 tons per 834m². It can be noted that the third scenario (20.266 tons/834m²) generated higher environmental impacts when compared to the other two scenarios (11.259 and 15.763 tons/834m²).

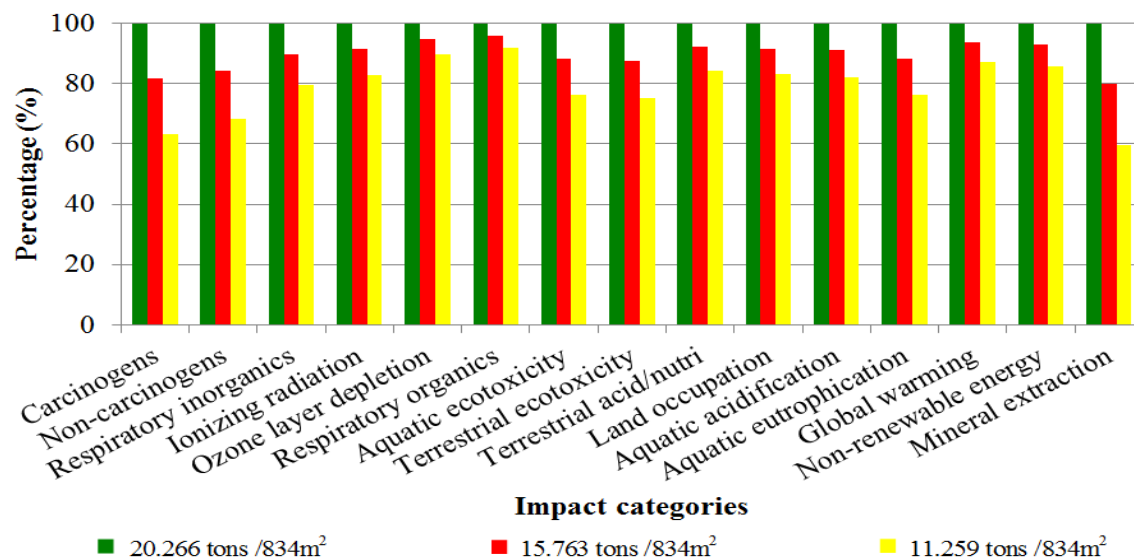
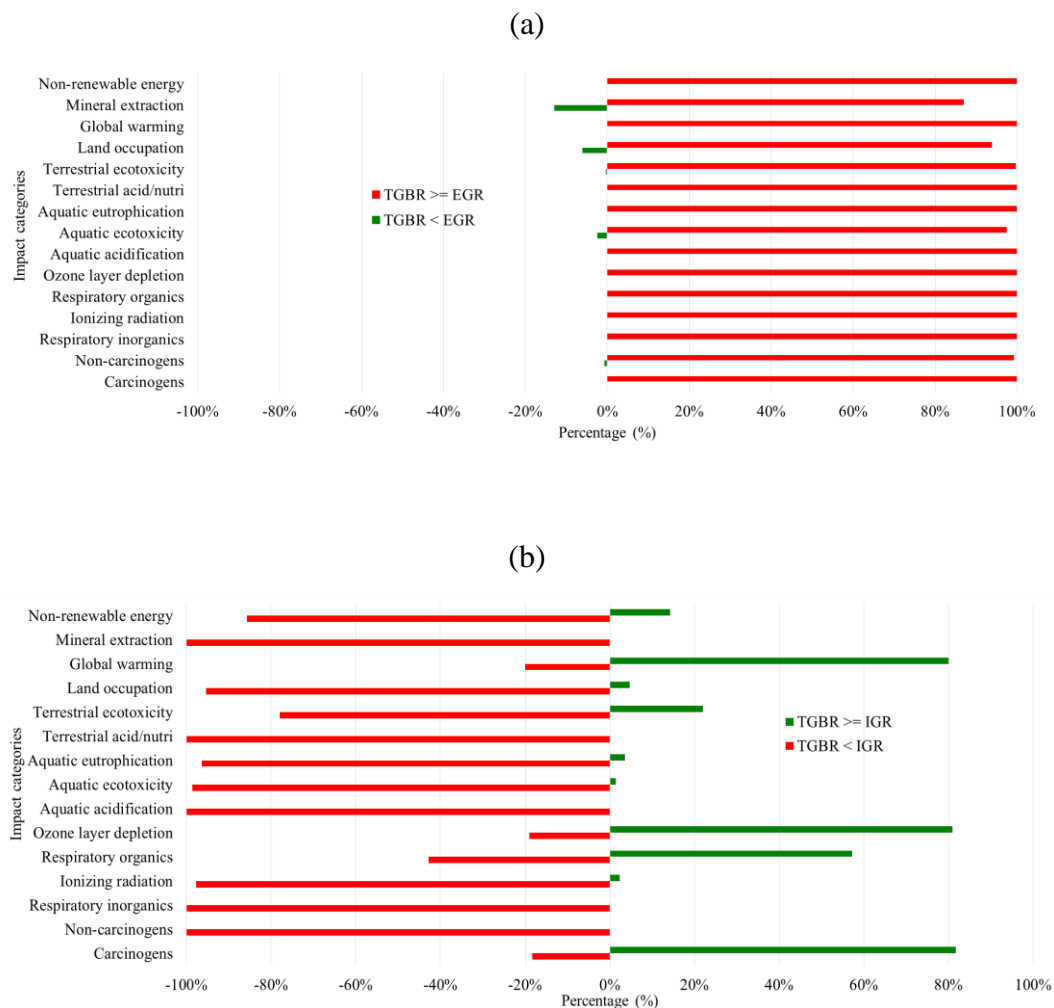


Figure 3-5: Sensitivity analysis for different amounts of rebar

3.4.4 Uncertainty analysis

While building an LCA model [52], uncertainties might be due to the quality of the data (incomplete or inaccurate), in particular the amounts of each material, transportation, and processes selected for assembling the roofs.

Björklund (2002) mentioned that an uncertainty analysis helps to “identify and quantify the uncertainty introduced into the results due to the cumulative effects of input uncertainty and data variability” [53]. In fact, a particular value might be highly inexact even if its contribution to the uncertainty of the overall result is irrelevant. One of the solutions to determine the uncertainty is Monte Carlo simulation [54]. Monte Carlo simulations were done in SimaPro with a fixed number of 1,000 runs, a stop factor of 0.005, and a confidence interval of 95%. **Figures 3-6 (a) and 6 (b)** show the uncertainty analysis for TGBR compared to EGR and IVR, respectively. **Figures 3-6 (c) and 6 (d)** present the uncertainty analysis results for the WRR compared to EGR and IGR, respectively. **Figure 3-6 (e)** shows the uncertainty analysis results for IGR and EGR.



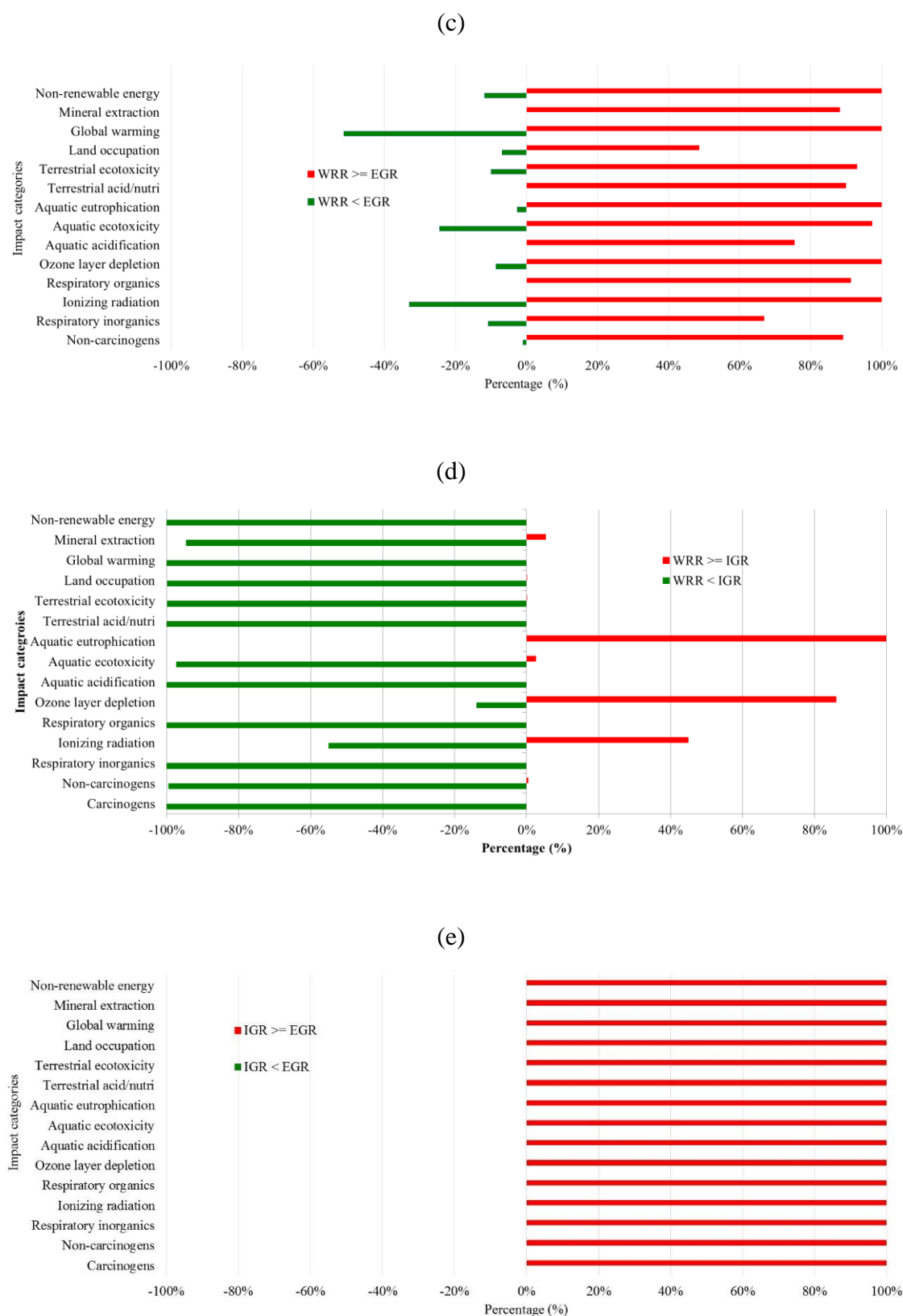


Figure 3-6: Uncertainty analysis for (a) TGBR compared to EGR (b) TGBR compared to IGR (c) WRR compared to EGR (d) WRR compared to IGR (e) EGR compared to IGR.

When comparing EGR to TGBR and to WRR in **Figures 3-6(a)** and **6(c)**, one can confirm that TGBR and WRR contributed more than EGR for all impact categories. The uncertainty analysis of TGBR compared to IGR in **Figure 3-6(b)** indicated that the impacts of IGR were higher for all impact categories, except for the ozone layer depletion, respiratory organics, global warming, and carcinogens. For these categories, the confidence interval was 81.0, 57.2, 80.0, and 81.7%, respectively. **Figure 3-6(d)** confirmed that WRR contributed more than IGR for two impact categories: ozone layer depletion and aquatic eutrophication. The uncertainty analysis for the EGR compared to IGR is represented in **Figure 3-6(e)**. This analysis confirmed with a 100% confidence interval that IGR contributed more than EGR to all potential impacts.

3.5 Conclusion

A cradle-to-gate Life Cycle Assessment was performed and the environmental performance of TGBR, WRR, EGR, and IGR have been evaluated. This was done to evaluate if VRs are truly better than TGBRs and WRRs from a life cycle perspective. As indicated by the results, the EGR had the least environmental impacts for all impact categories. When looking at the contribution of roof components to the potential environmental impacts, concrete, rebar, waterproof membrane, and thermal insulation were the main contributors. Perlite was also a main contributor for the land occupation category for the VRs. Sensitivity and uncertainty analyses were also performed to check the robustness of the results.

3.6 Limitation and Perspectives

The current paper is limited to a cradle-to-gate environmental impact assessment of TGBR, WRR, EGR, and IGR. Future research will focus on a full LCA including the use (thermal insulation effects, energy consumption, water retention, and even pollutant extraction from the atmosphere, etc.) and the end-of-life phases.

3.7 Acknowledgement

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3.8 References

- [1] Liu KY, Baskaran A. (2005). Using Garden Roof Systems to Achieve Sustainable Building Envelopes. Institute for Research in construction: 65.
- [2] Djedjig R, Bozonnet E, Belarbi R. (2013). Integration of a green envelope model in a transient building simulation program and experimental comparison http://www.ibpsa.org/proceedings/BS2013/p_1225.pdf Accessed on August 21, 2015.
- [3] Christian JE, Petrie TW. (1996). Sustainable Roofs with Real Energy Savings. <http://www.osti.gov/scitech/servlets/purl/45119> 3. Accessed on August 21, 2015.
- [4] Terjung WH, O'Rourke PA. (1981). Relative influence of vegetation on urban energy budgets and surface temperatures, Boundary Layer Meteorology, U.S.A.
- [5] Scherba, A., Sailor, D. J., Rosenstiel, T. N., & Wamser, C. C. (2011). Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. Building and Environment, 46(12), 2542-2551. doi: <http://dx.doi.org/10.1016/j.buildenv.2011.06.012>.
- [6] Terjung WH, O'Rourke PA. (1981). Energy input and resultant surface temperatures for individual urban interfaces, selected latitudes and seasons. Meteorology and Atmospheric Physics, U.S.A.
- [7] Moran A, Hunt B, Jennings G. (2003). North Carolina field study to evaluate green roof runoff quantity, runoff quality, and plant growth. <http://www.bae.ncsu.edu/greenroofs/ASAE2003paper.pdf>. Accessed on July 20, 2015.
- [8] Wong NH, Chen Y, Ong CL, Sia A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. Building and Environment 38:261–270. Doi:10.1016/S0360-1323(02)00066-5.
- [9] Carter TL, Rasmussen TC. (2006). Hydrologic behavior of vegetated roofs. J. Am. Water Resour. Assoc. 42 (5), 1261–1274.
- [10] DeNardo JC, Jarrett AR, Manbeck HB, Beattie DJ, Berghage RD. (2005). Stormwater mitigation and surface temperature reduction by green roofs. Trans. ASAE 48 (4), 1491–1496. Doi: 10.13031/2013.19181.

- [11] Dunnett N, Nagase A, Hallam A. (2008). The dynamics of planted and colonising species on a green roof over six growing seasons 2001–2006: influence of substrate depth. *Urban Ecosystem*. 11: 373–384. Doi 10.1007/s11252-007-0042-7.
- [12] Dunnett N, Nagase A, Booth R, Grime P. (2008). Influence of vegetation composition on runoff in two simulated green roof experiments. *Urban Ecosyst*. 11: 385–398. Doi: 10.1007/s11252-008-0064-9.
- [13] Getter KL, Rowe DB, Andresen, J.A. (2007). Quantifying the effect of slope on extensive green roof stormwater retention. *Ecol. Eng*. 31: 225–231.
- [14] VanWoert ND, Rowe DB, Andersen JA, Rugh CL, Fernandez RT, Xiao L. (2005). Green roof storm water retention: effects of roof surface, slope and media depth. *J. Environ. Qual*. 34:1036–1044. Doi:10.2134/jeq2004.0364.
- [15] Liu K, Baskaran B. (2003). Thermal performance of green roofs through field evaluation. Proceedings for the first North American green roof infrastructure conference, Chicago, pp. 1–10.
- [16] Rood flooding. (2013). Retrieved from <http://floodlist.com/asia/floods-lebanon>. Accessed on September 22, 2015.
- [17] Rood flooding. (2013). Retrieved from <http://www.dailystar.com.lb/News/Lebanon-News/2013/Dec-05/239982-heavy-rains-trigger-floods-block-beirut-airport-road.ashx>. Assessed on September 22, 2015.
- [18] Ministry of Energy and Water. (2010). Policy paper for the electricity sector. <http://climatechange.moe.gov.lb/viewfile.aspx?id=121>. Accessed on August 28, 2015.
- [19] Dunnett, N. Kingsbury, N. (2004). *Planting Green Roofs and Living Walls*. Timber Press, Inc., Portland, OR.
- [20] Getter K.L., and Rowe, D. B. (2006). The Role of Extensive Green Roofs in sustainable Development. *Hort Science*, 41(5), 1276–1285.
- [21] Jacobsen B. (2009). <http://wsp.arizona.edu/sites/wsp.arizona.edu/files/uawater/documents/Fellowship200809/Jacobsen.pdf>. Accessed on September 23, 2015.
- [22] International Organization for Standardization (ISO). (2006). *Environmental management - life cycle assessment - principles and framework 14040*. Geneva.

- [23] International Organization for Standardization (ISO). (2006). Environmental management - life cycle assessment - requirements and guidelines 14044. Geneva.
- [24] Jeswani HK, Azapagic A, Schepelmann P, Ritthoff M. (2010). Options for broadening and deepening the LCA approaches. *Journal of Cleaner Production*: 18(2), 120-127.
- [25] Bozorg Chenani, S., Lehvävirta, S., & Häkkinen, T. (2015). Life cycle assessment of layers of green roofs. *Journal of Cleaner Production*, 90, 153-162. Doi: <http://dx.doi.org/10.1016/j.jclepro.2014.11.070>.
- [26] Ottel , M., Perini, K., & Haas, E. M. (2014). 19 - Life Cycle Assessment (LCA) of green fa ades and living wall systems. In F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha & A. d. Magalh es (Eds.), *Eco-efficient construction and building materials* (pp. 457-483) Woodhead Publishing. Doi: <http://dx.doi.org/10.1533/9780857097729.3.457>.
- [27] Peri, G., Traverso, M., Finkbeiner, M., & Rizzo, G. (2012). The cost of green roofs disposal in a life cycle perspective: Covering the gap. *Energy*, 48(1), 406-414. Doi: <http://dx.doi.org/10.1016/j.energy.2012.02.045>.
- [28] Kosareo L, Ries R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and Environment* 42, 2606–2613.
- [29] Saiz S, Kennedy C, Bass B, Resnail K. (2006). Comparative Life Cycle Assessment of Standard and Green Roofs. *Environ. Sci. Technol.* 40: 4312-4316.
- [30] El-Fadel RH, Hammond GP, Harajli HA, Jones CI, Kabakian VK, Winnett AB. (2010). The Lebanese electricity system in the context of sustainable development. *Energy Policy* 38(2): 751-761. Doi:10.1016/j.enpol.2009.10.020.
- [31] Kabakian, V., McManus, M. C., & Harajli, H. (2015). Attributional life cycle assessment of mounted 1.8 kWp monocrystalline photovoltaic system with batteries and comparison with fossil energy production system. *Applied Energy*, 154, 428-437. Doi: <http://dx.doi.org/10.1016/j.apenergy.2015.04.125>.
- [32] Dahdal, R. (2014). Life Cycle Assessment of solar water heaters in Lebanon: an environmental comparison. Dissertation, University of Balamand.
- [33] Defining Life Cycle Assessment <http://www.gdrc.org/uem/lca/lca-define.html>. Accessed on July 20, 2015.

- [34] Educational Community for Homeowners. (2016). Guide to solar-reflective paints for energy-efficient homes. Retrieved from <http://www.echo-ca.org/article/guide-solar-reflective-paints-energy-efficient-homes>. Accessed on June 17, 2016.
- [35] She N, Pang J. (2010). Physically based green roof model. *J Hydrologic Eng* 15(6):458-464.
- [36] Eumorfopoulou E, Aravantinos D. (1998). The contribution of a planted roof to the thermal protection of buildings in Greece. *Energy and Buildings* 27, 20-36.
- [37] Soprafix HP. (2015). <http://www.soprema.com/%5Bi18n-termpath-raw%5D/soprafix-hp> Accessed on August 30, 2015.
- [38] Sopranature. (2011). <http://www.soprema.ca/en/content/10/sopranature.aspx>. Accessed on August 30, 2015.
- [39] Teemusk A, Mander Ü. (2007). Rainwater runoff quantity and quality performance from a green roof: the effects of short-term events. *Ecol Eng* 30(3): 271-277. Doi: 10.1016/j.ecoleng.2007.01.009.
- [40] Alexander R. (2004). Green roof grow with brown compost, *BioCylce* 45(9): 55-56.
- [41] Czemieli Berndtsson, J. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, 36(4), 351-360. doi: <http://dx.doi.org/10.1016/j.ecoleng.2009.12.014>.
- [42] Coma, J., Pérez, G., Solé, C., Castell, A., & Cabeza, L. F. (2016). Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renewable Energy*, 85, 1106-1115. doi: <http://dx.doi.org/10.1016/j.renene.2015.07.074>.
- [43] Dunnett N, Kingsbury N. (2004). *Planting green roofs and living walls*. Timber Press, Portland.
- [44] Country energy efficiency and renewable energy demonstration for the recovery of Lebanon. (2012). Retrieved from <http://www.medsolarproject.com/index.php/en/undp>. Accessed on June 17, 2016.
- [45] University of Balamand. (2016). Civil engineers and technicians. Retrieved from <http://www.balamand.edu.lb/DirectoryContacts/Pages/default.aspx>. Accessed on June 17, 2016.
- [46] Ecoinvent. (2015). <http://www.ecoinvent.org/>. Accessed on June 17, 2016.

- [47] Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E. (2013). Introduction to LCA with SimaPro. <http://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf>. Accessed on July 20, 2015.
- [48] Joliet O, Margni M, Charles R, Humbert S, Jérôme P, Rebitzer G, and Rosenbaum R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. *Int J LCA* 8(6): 324-330.
- [49] Lamnatou, C., & Chemisana, D. (2015). Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle-based environmental indicators. *Building and Environment*, 93, Part 2, 376-384. Doi: <http://dx.doi.org/10.1016/j.buildenv.2015.06.031>.
- [50] Maurice B, Frischknecht R, Coelho-Schwartz V, Hungerbühler K. (2000). Uncertainty analysis in life cycle inventory. Application to the production of electricity with French coal power plants. *Journal of Cleaner Production* 8: 95-108.
- [51] University of Balamand. (2016). Landscape experts. Retrieved from <http://www.balamand.edu.lb/DirectoryContacts/Pages/default.aspx>. Accessed on June 17, 2016.
- [52] Kohler N., Lützkendorf T. (2002). Integrated Life Cycle Analysis. *Building Research & Information*: 30(5), 338–348. Doi: 10.1080/09613210110117584.
- [53] Björklund A.E. (2002). Survey of approaches to improve reliability in LCA. *International J LCA* 7 (2), 64-72. Doi: <http://dx.doi.org/10.1065/Ica2001.12.071>.
- [54] Morgan MG, Henrion M. (1990). *Uncertainty*. Cambridge university press. United Kingdom.

CHAPTER 4 REAL-TIME TEMPERATURE MONITORING FOR TRADITIONAL GRAVEL BALLASTED ROOF AND EXTENSIVE GREEN ROOF: A LEBANESE CASE STUDY

4.1 Abstract

The aim of this paper is to study and compare the temperature profile and energy performance of traditional and Vegetative Roofs (VRs) during winter season in Lebanon, a country in the Middle East. Three roof mockups were installed on the rooftop of the Chemical Engineering Department at the University of Balamand: a Traditional Gravel Ballasted Roof (TGBR) and two Extensive Green Roofs (EGRs) with different substrate depth and composition. Each minute, the temperature of air, on TGBR surface, and at different depths of EGR was recorded. The daily cooling and heating demands were also calculated. Results confirmed that VRs protect the roof membrane from high temperature fluctuations and decrease air temperature by a factor of one and a half during sunny winter days ($T_{air\ max} = 32^{\circ}C$). Findings of this study also showed that the total cooling demand of EGR decreased by 90% compared to TGBR.

4.2 Introduction

Vegetative Roofs (VRs) are gaining popularity due to many benefits compared to Traditional Gravel Ballasted Roofs (TGBRs). In particular, VRs have positive impacts on the quality of ambient air through the removal of air pollutants by plants [1-3]. From an energetic perspective, the use of such types of roofs can be very efficient. This is especially the case in summertime when VRs could reduce temperature fluctuations through the direct shading of plant canopy and cool the ambient air by consuming solar heat gain for transpiration and photosynthesis processes [4]. Moreover, VRs emit less long wave radiation due to their lower surface temperature. As a result, the Urban Heat Island (UHI) magnitude is reduced [5-9] and the energy consumption in urban areas is decreased [10-12]. In addition, the different layers of VRs block the solar radiation from reaching the concrete membrane, thus lowering its temperature and also reducing temperature fluctuations [13, 14]. However, TGBRs absorb solar radiation and the concrete membrane is heated up by the sun during the day and cooled down at night. These daily temperature fluctuations could crack the roof membrane and reduce its durability if occurring frequently [15-17]. Furthermore, VRs have an aesthetic appeal [18,

19], can mitigate noise pollution [14], and provide food as well as a safe habitat for many kinds of animals and invertebrates [20]. Some of the indirect VRs advantages are reducing the cost of house insurance [21] and increasing the building's value [22].

There are two main types of VRs: intensive and extensive. The Intensive Green Roof (IGR) has a thick growing medium (>20 cm) whereas the Extensive Green Roof (EGR) has a thin substrate (<20 cm) [23, 24] and is more suitable for existent buildings since no additional roof support material is required [25].

Several researches have been conducted on the temperature regime of VRs compared to TGBRs to prove that VRs protect the roof membrane from extreme temperature fluctuations [7, 26]. Studies were also done to assess and analyze VR's heat transfer capacity and its impact on the temperature fluctuations reduction and on the buildings' energy consumption [12, 15, 27-32].

Jaffal *et al.* (2012) studied the energy performance of VRs compared to TGBRs in a temperate oceanic climate concluding that average indoor air temperature under TGBRs and VRs differed only by 1.5°C in a sunny winter day, and was the same (19.0°C) in a typical winter day [26]. Another aspect investigated by Wong *et al.* (2003) was the thermal benefits of VRs in a tropical climate acting as a cooling system in warmer days where maximum temperature on hard surface was 57.0°C compared to 36.0°C under planted soil [7]. Alternatively, the results of a simulation study done by Gagliano *et al.* (2015) established that an insulated EGR significantly decreases the cooling energy needs of a residential building and mitigates the UHI effect in mild Mediterranean areas [28]. To date, no study has yet been explored in the literature about the temperature profile of EGRs with different substrate's composition as suggested in this study and elaborated in the next section.

VRs are recent technologies in Lebanon. So far, only a total of five GRs have been installed in the country. The one occupying the largest surface area was installed at the Central Bank of Lebanon, Beirut branch (834m^2), while another one was implemented on the rooftop of a private house (200m^2). The installation of VRs could be an interesting option for Lebanon, a country characterized by moderate temperatures. Such roofs could also be a plausible solution to the Lebanese energy crisis and lack of a clear water management plan. In particular, the Lebanese electricity and water sectors are facing major problems since the civil war (1975-1990) [33-35]. The "Electricité du Liban" (EDL), a public institution under the control of the Ministry of Energy and Water, was and still is mandated the responsibility of the generation,

transmission, and distribution of electrical energy in Lebanon [36]. Despite the major rehabilitation plan, blackouts are common all around the year in almost all the Lebanese cities [38, 39].

This research, a first of its kind in the Middle East region, focuses on i) characterizing and analyzing the temperature profile of a TGBR mockup and two EGR mockups with different substrate depths and composition in winter season and ii) determining the installation and energy savings of an EGR.

4.3 Material and methods

4.3.1 Description of the experimental bench: different types roofs mockups

Based on a recent study comparing the environmental impacts of traditional gravel ballasted, white reflective, extensive, and intensive green roofs in the Lebanese context, it was clearly shown that extensive green roofs had the lowest environmental impacts [40]. Therefore, a TGBR and two EGR roof mockups of square shape (70 cm x 70 cm) were installed on the rooftop of the Chemical Engineering Department at the University of Balamand, in the region of El Koura, North Lebanon (34°31'N, 35°50'E). The two EGR mockups were EGR8 (i.e. with a substrate depth of 8 cm) and EGR16 (i.e. with a substrate depth of 16 cm) (**Figure 4-1**).

The TGBR mockup consisted of the following layers: roof assembly, thermal insulation layer, waterproof membrane, filter sheet, and exterior layer made of pebbles. The roof assembly was a mixture of hollow concrete blocks, rebar, and mixed concrete. The EGR mockups were each installed using the following layers: roof assembly, thermal insulation layer, waterproof membrane, root resistant barrier, drainage layer, filter sheet, growing medium, and vegetation. The roof assembly was the same as for TGBR mockup. As for the substrate, it entailed oil, peat, alumina, pumice, and organic fertilizer. This substrate composition is studied for the first time in this study. The vegetation layer was pre-cultivated elements. In fact, hollow concrete blocks, rebar, concrete, thermal insulation boards, waterproof membrane, and filter sheet were supplied from local suppliers. For the pebbles, plants, and the components of the growing medium, they were provided by the landscaping, gardening and agriculture department at the University of Balamand. As for the anti-root and the drainage layers, they were delivered from Zinco, Germany [41]. The amount of each component constituting the three mockups is indicated in **Table 4-1**.



Figure 4-1: Mockups on the rooftop of the chemical engineering building: (a) TGBR (b) EGR8 (c) EGR16

Table 4-1: Components of TGBR, EGR8, and EGR16 mockups

	TGBR	EGR 8	EGR16
	1 Brick	1 Brick	1 Brick
Roof assembly	Steel: 6.61 kg Concrete: 0.13 m ³	Steel: 6.61 kg Concrete: 0.13 m ³	Steel: 6.61 kg Concrete: 0.13 m ³
Thermal insulation	Styrofoam: 0.5 m ²	Styrofoam: 0.5 m ²	Styrofoam: 0.5 m ²
Waterproof	SBS waterproof	SBS waterproof	SBS waterproof
Root resistant barrier	N.D.	ZinCo WSF 40	ZinCo WSF 40
Drainage	N.D.	ZinCo FD 40-E	ZinCo FD 40-E
Filter	ZinCo SF	ZinCo SF	ZinCo SF
		Soil: 11.20 kg Peat: 21.45 kg	Soil: 25.60 kg Peat: 41.25 kg
Growing medium	N.D.	Alumina: 28.80 kg Pumice: 5.13 kg Fertilizer: 0.07 kg	Alumina: 0.00 kg Pumice: 19.87 kg Fertilizer: 0.15 kg
		<i>Rosemary</i> <i>Lavender</i> <i>Alyssum</i>	<i>Rosemary</i> <i>Lavender</i> <i>Alyssum</i>
Vegetation	N.D.	<i>Argyranthemum madeira</i> <i>Marguerite daisy</i> <i>Gazania rigens</i> <i>Lobularia maritima</i>	<i>Argyranthemum madeira</i> <i>Marguerite daisy</i> <i>Gazania rigens</i> <i>Lobularia maritima</i>
Pebbles	10 cm	N.D.	N.D.

N.D.: Material or component not needed for the particular roof mockup.

The different mockups were not covered, at a distance of 40 cm from each other, and about 10 m above the ground level. During the measurement period (January 14th until March 31st,

2016), the plants covered around 45% of the roof surface of both EGR8 and EGR16 as the weather conditions prevented a further development of plants.

4.3.2 Sensors installation and measurements

The internal temperature of TGBR, EGR8, and EGR16 was measured using a total of 12 thermocouples from Mesurex (France) [42], and recorded with the measurement and control datalogger CR1000 connected to a channel relay multiplexer AM 16/32B produced by Campbell Scientific (United States) [43, 44]. Air temperature was monitored using a waterproof temperature sensor ordered from Gemini Data Loggers (United Kingdom) [45]. All temperature measurements were recorded every minute. Air temperature could be monitored on the leaf canopy and at different heights but due to the partial plant coverage, it was only measured at 110 cm height above the surface of the mockups. As shown in **Figure 4-2.a**, temperature probes in the TGBR mockup were mounted between thermal insulation layer and waterproof membrane in addition to between filter sheet and pebbles layer. For EGR mockups (**Figures 4-2.b & 2.c**), temperature sensors were installed between thermal insulation layer and waterproof membrane as well as between filter sheet and substrate layer. Likewise, temperature sensors were set up at depths of 2, 4, and 6 cm in substrate layer of EGR8 mockup, and at depths of 1, 6, and 11 cm in substrate layer of EGR16 mockup.

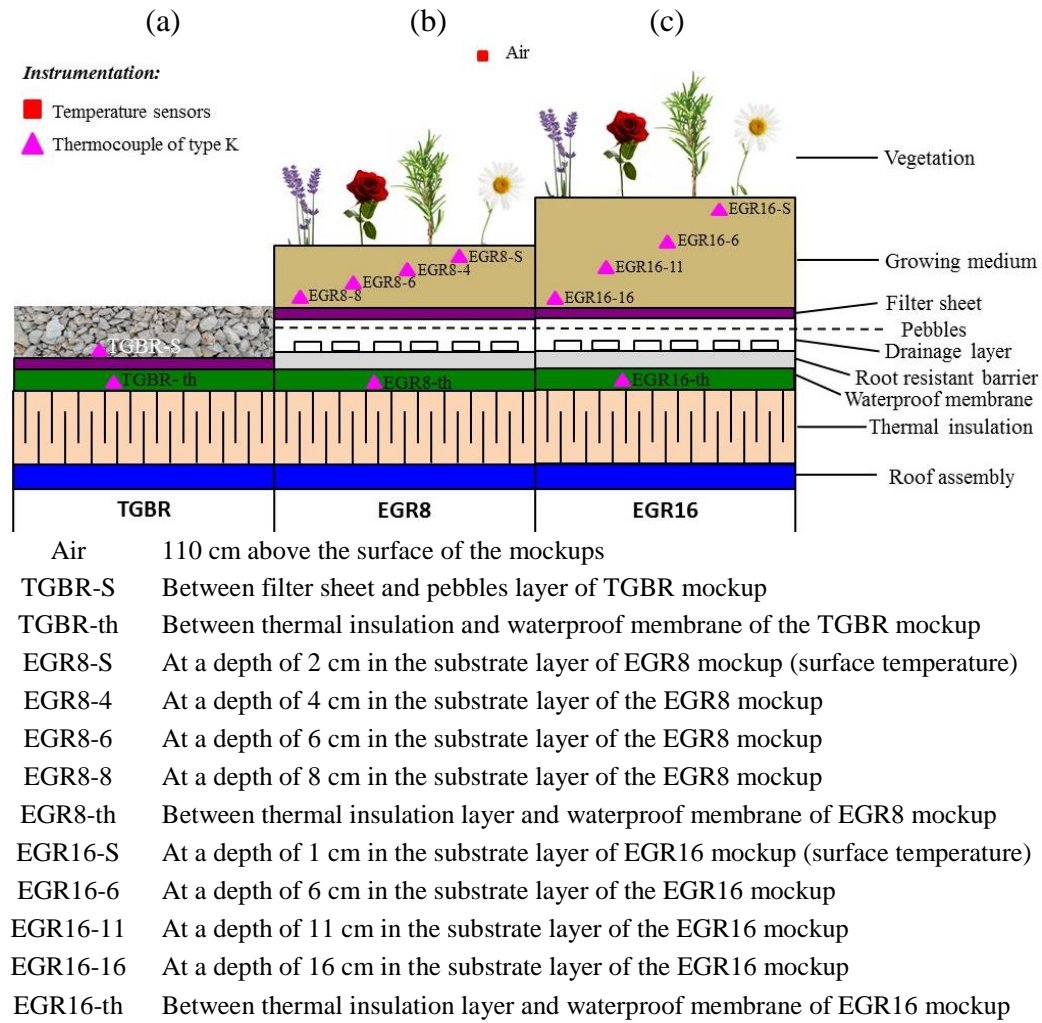


Figure 4-2: Moisture sensors location for: (a) TGBR (b) EGR8 and (c) EGR16 mockups

4.3.3 Heating and Cooling Degree Day(s)

A Degree Day (DD) is an indicator of the household heating or cooling consumption for a specific period of time [46]. Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) could be computed using hourly, daily, monthly or seasonal temperature data. In this study, DDs were calculated using average daily temperatures. In cold days, when average daily temperature falls below the comfort level (base temperature) heating is needed; while in warm days, when average daily temperature rises above the comfort level, cooling is needed. The base temperature was considered 18 degrees Celsius in cold days and 21 degrees Celsius in hot days [47]. HDDs and CDDs were obtained based on **Equations 1.a and 1.b**, while **Equation 2** was used to convert the HDDs and CDDs to heating and cooling costs.

The occupancy factor in **Equation 2** is assumed to be 70% in residential buildings since specific rooms are heated up or cooled down, and 100% in hotels or hospitals as the whole structure is maintained at comfort level. Another element in **Equation 2** is the price/cost of

electricity where one kWh of electricity costs 0.17 US\$ when provided by EDL and 0.32 US\$ when provided by private generators (PGs) [37, 48]. More to the point and despite the major rehabilitation plan for the Lebanese electricity sector since the civil war, electricity demand still exceeds electricity supplied and blackouts can reach 13 hours per day in some cities. Therefore, Lebanese citizens still use back-up PG to ensure their electricity needs [37].

$$HDD = T_{base} - T_A \quad (a)$$

$$CDD = T_A - T_{base} \quad (b)$$

HDD = Heating Degree Day

CDD = Cooling Degree Day

T_{base} = Base temperature in Celsius degree (18°C for HDD and 21°C for CDD)

T_A = Average daily temperature in degree Celsius

Equation 4-1: Degree Day formulas: (a) Heating Degree Day (b) Cooling Degree Day [38]

$$E = DD \times F \times P$$

E = Cost of electricity for heating or cooling (US\$)

DD = Heating Degree Day or Cooling Degree Day

F = Occupancy effect factor (0.70)

P = Price of electricity (EDL: US\$ 0.17/kWh; PG: US\$ 0.32/kWh)

Equation 4-2: Cost calculation using Degree Day

4.4 Results and discussion

4.4.1 Temperature profiles

Temperature profiles from January until end of March, 2016 are depicted in **Figures 4-3 to 6** below. **Figure 4-3** represents the average of daily temperatures which is the difference between maximum and minimum daily temperatures divided by two versus the time on a daily basis. Results showed that during warmer days (e.g. March 2nd, 2016), the substrate temperature was lower than that of the TGBR surface. During colder winter days (e.g. January 26th, 2016), EGR8 and EGR16 daily average substrate temperature values were similar to that of the TGBR surface mostly due to partial plant coverage.

Figure 4-4 represents the amplitudes of daily temperatures which is the difference between maximum and minimum daily temperatures versus the time on a daily basis. Higher values were recorded for EGR8 and EGR16 surfaces compared to TGBR surface. As a result, EGR8 and EGR16 surfaces were warmer during the day and cooler during the night compared to

TGBR surface. This temperature fluctuation on EGR8 and EGR16 surfaces could be due to the negligible "mask effect" of the vegetation layer [26]. Moreover, the temperature under the EGR8 and EGR16 substrates was not affected by the daily temperature fluctuation on the EGR surfaces. In fact, a further look into the figures illustrates this for all the measurement period where the average daily temperature amplitudes was 4.02°C under the EGR8 substrate, 2.87°C under the EGR16 substrate, 4.89°C on TGBR surface, and 10.14°C in the air. Consequently, the temperature fluctuations were effectively reduced when using EGR8 and EGR16.

The highest recorded temperature values were 26.18°C for air, 33.98°C for TGBR's surface, 24.24°C for under EGR8 substrate, and 23.36°C for under EGR16 substrate. This indicates that the highest temperature values of air and on TGBR surface were greater than that of under EGR substrates.

Figure 4-5 represents the temperature variation of EGR8, EGR16, TGBR, and air during cold and sunny days. During cold winter days, temperature under EGR8 and EGR16 substrates were higher than that of air and TGBR surface ($T_{\text{EGR8-th}} = 22.07^{\circ}\text{C}$; $T_{\text{EGR16-th}} = 14.93^{\circ}\text{C}$; $T_{\text{Air}} = 11.32^{\circ}\text{C}$, and $T_{\text{TGBR-S}} = 12.47^{\circ}\text{C}$). As shown in **Figure 4-5**, temperature under EGR8 and EGR16 substrates was colder than that of air and TGBR surface in sunny winter days ($T_{\text{EGR8-th}} = 20.74^{\circ}\text{C}$; $T_{\text{EGR16-th}} = 20.81^{\circ}\text{C}$; $T_{\text{Air}} = 23.56^{\circ}\text{C}$, and $T_{\text{TGBR-S}} = 23.35^{\circ}\text{C}$). This indicates that VRs can store heat in colder days and cool the roof membrane in warmer days. These values were similar to the ones obtained by Jaffal *et al.* (2012) [26]. Jaffal *et al.* (2012) stated that, in a cold winter day, the substrate temperature was warmer than air temperature by 5.6°C compared to by 10.35°C for EGR8 and by 3.61°C for EGR16 in this study. Moreover, Jaffal *et al.* (2012) found that, in a sunny winter day, the substrate was colder than the air temperature by 2.9°C compared to by 2.82°C for EGR8 and by 2.75°C for EGR16 in this study.

Figure 4-6 represents monthly variation of temperature amplitudes. Results revealed that the temperature fluctuations for air and on TGBR surface were higher than under EGR8 and EGR16 substrates. The fluctuations were more noticeable during February and March 2016, which were sunnier winter days. Results also showed that the temperature amplitudes under the EGR16 substrate were less than that under the EGR8 substrate. In the same study of Jaffal *et al.* (2012) [26], the temperature variation for VRs was lower than that of TGBRs during typical cold winter and sunny winter days. Results in this paper are also in agreement with Jim and Tsang [31]. He *et al.* (2015) [49] found that EGR has an important cooling effect during sunny daytime; it was therefore acting as a heat sink in the daytime and heat insulation at night. In contrast, TGBRs act as a heat source during sunny daytime and a heat sink during the night.

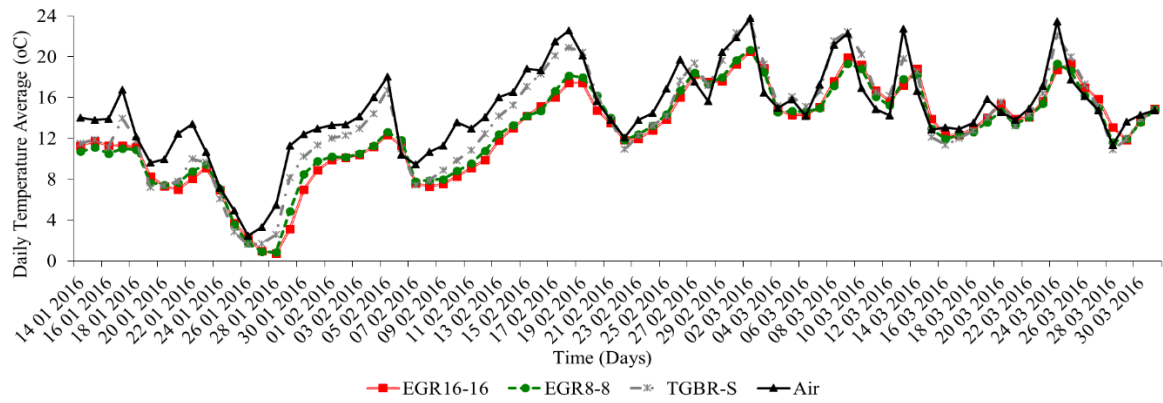


Figure 4-3: Daily average temperatures

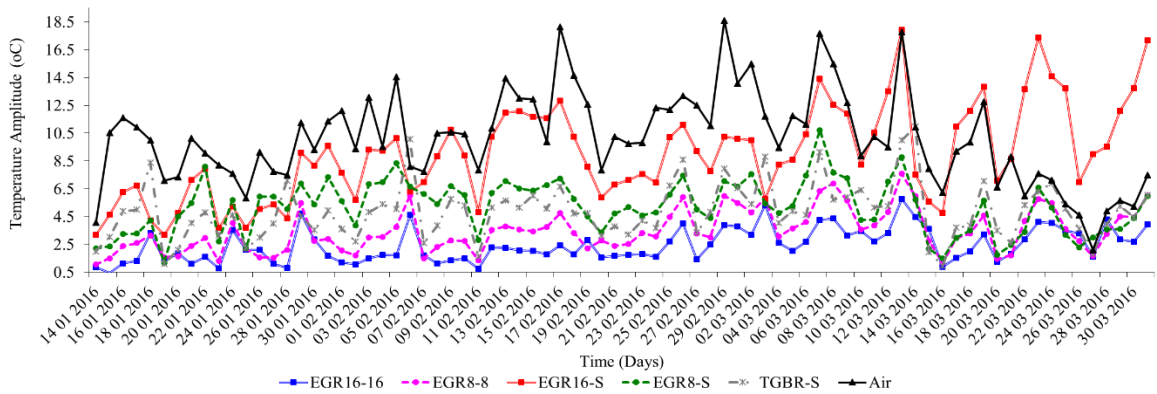


Figure 4-4: Daily temperature amplitude

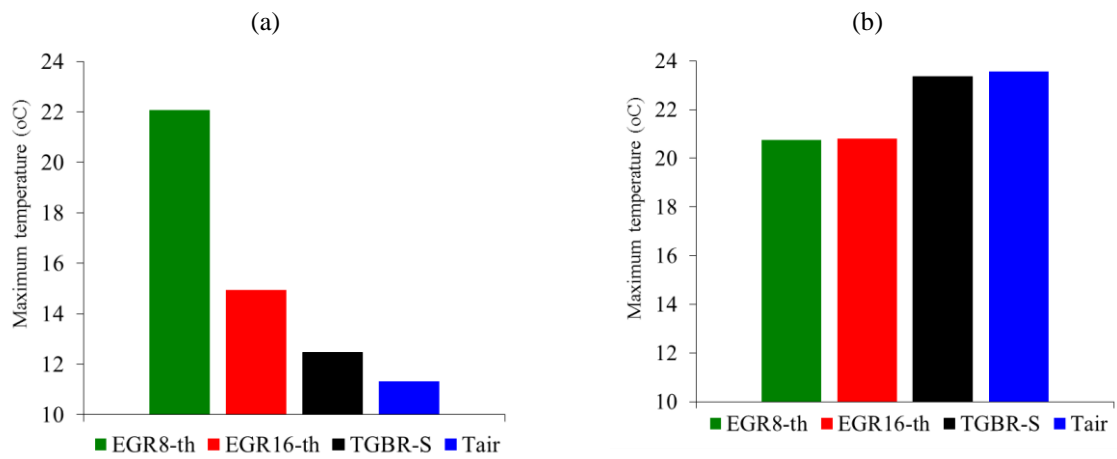


Figure 4-5: Temperature variation for EGR8, EGR16, TGBR, and air during (a) cold days and (b) warm days

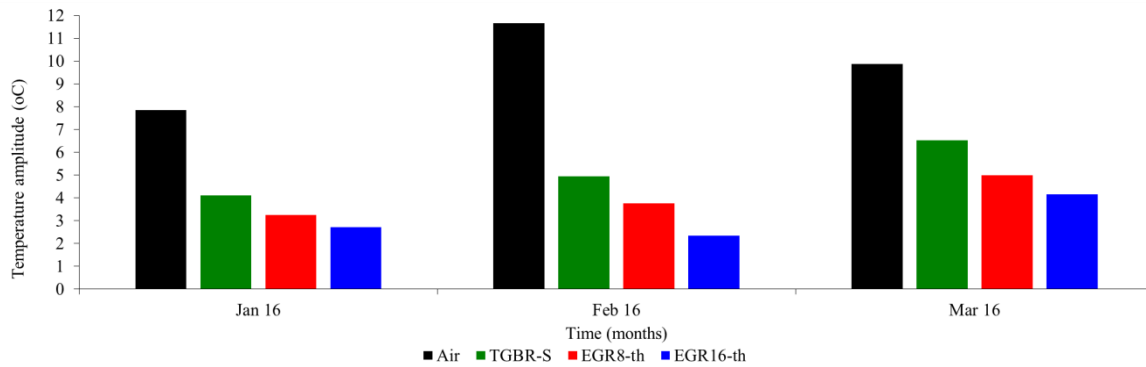


Figure 4-6: Monthly temperature amplitudes variation (difference between maximum and minimum daily temperatures)

4.4.2 Temperature profile for different substrate depths

The heat diffusion process was studied by measuring the growing medium's temperature for different depths, namely EGR8-S and EGR16-S (on the substrate surface), EGR8-8, EGR8-6, EGR8-4, EGR16-16, EGR16-11, and EGR16-6. The decrease in temperature fluctuations is one of the important reasons to install a VR. This effect is significant in Mediterranean and tropical climatic zones [7, 50]. **Figures 4-7 and 4-8** show the daily variation of the temperature amplitudes at different depths of EGR8 and EGR16 substrates, respectively. For both cases, a decrease in the temperature fluctuations was clearly observed.

For instance, in sunny winter days (e.g. from the 17th until the 19th of February 2016), the temperature fluctuated by 6.38°C for air, 7.97°C for EGR8-4, 5.86°C for EGR8-6, 5.52°C for EGR8-8, 3.85°C for EGR16-6, 3.11°C for EGR16-11, and 3.34°C for EGR16-16. Consequently, in sunny winter days, temperature fluctuations were reduced by 13% for EGR8 substrate and by 48% for EGR16 substrate.

In typical winter days (e.g. between 20th and 23rd of January 2016), temperature values fluctuated by 6.32°C for air, 8.70°C for TGBR surface, 6.92°C for EGR8-4, 5.25°C for EGR8-6, 3.91°C for EGR8-8, 3.00°C for EGR16-6, 2.94°C for EGR16-11, and 3.17°C for EGR16-16. As a result, in typical winter days, TGBR surface temperature fluctuations were reduced by 55% and 64% due to EGR8 and EGR16 substrates respectively. While EGR8 and EGR16 substrates abridged air temperature fluctuations by 38% and 50% respectively. Despite a few studies are oriented toward the Middle East and no study is dedicated to a moderate Mediterranean climate such as Lebanon, the outcomes of this study are in coherence with the findings of Fioretti *et al.* (2010) [15] who investigated energy and water management performances of VRs in a cool and rainy Mediterranean climate. Fioretti *et al.* (2010) found

that the temperature of VRs was lower than the temperature of TGBRs due to the plant shading and evapotranspiration process. Results of the study done by Jim and Tsang (2011) [31] confirmed that, on winter sunny days, 10 cm of a substrate layer was enough to diminish temperature fluctuations since in day time, the soil stores solar radiation and releases it in night time. On a rainy day, the substrate layer absorbs the rainwater to enhance the soil heat capacity. In this study, the heat diffusion process designated by the thermal insulation effect of the growing medium can be achieved by approximately 6 cm soil. Accordingly, a thin soil layer was adequate to prevent the heat from diffusing into the building.

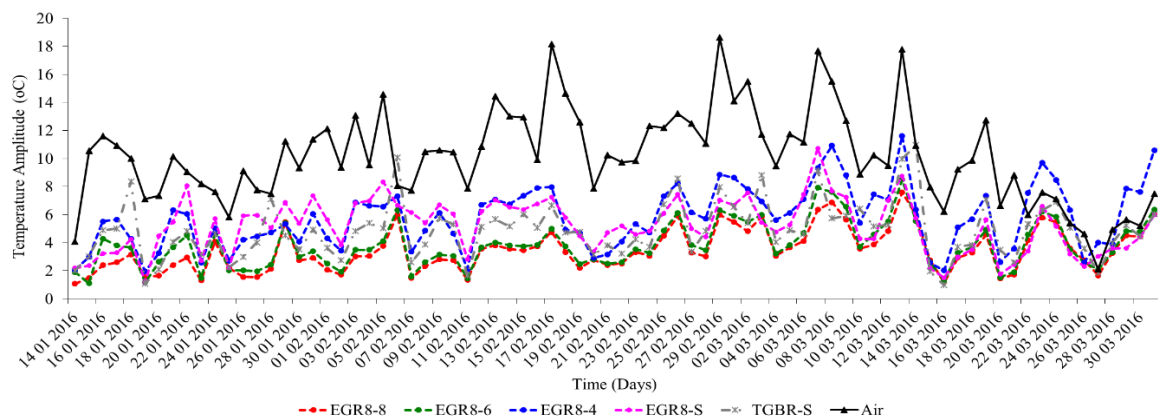


Figure 4-7: Variation of the temperature amplitudes for EGR8's substrate

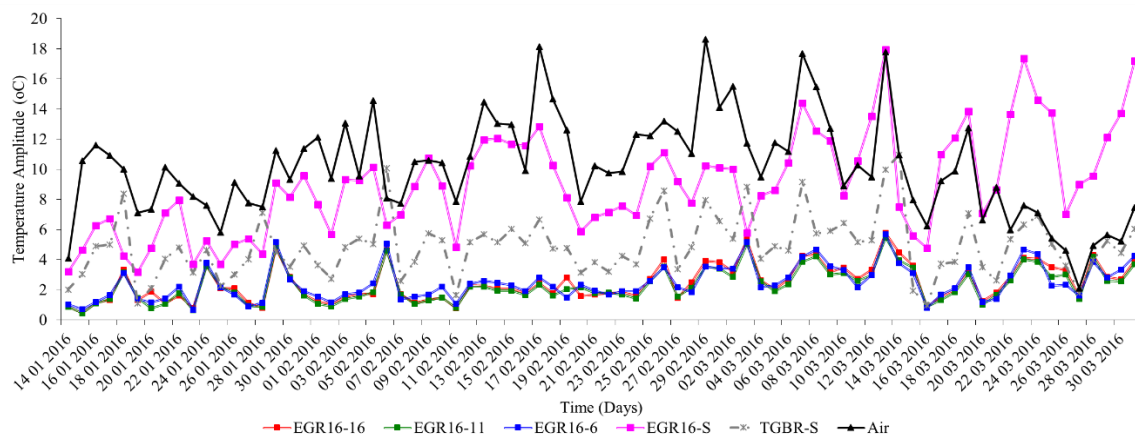


Figure 4-8: Variation of the temperature amplitudes for EGR16's substrate

4.4.3 Temperature profile in typical days

4.4.3.1 Typical cold winter day

In a typical cold winter day, recorded temperatures on an hourly basis (**Figure 4-9**) were between 2.16°C and 7.99°C for air (amplitude of 5.82°C), between 1.71°C and 3.96°C on TGBR

surface (amplitude of 2.25°C), between 2.68°C and 4.87°C under EGR8 substrate (amplitude of 2.19°C), and between 3.07°C and 5.17°C under EGR16 substrate (amplitude of 2.10°C). A further look into the data, elaborates the following: for EGR8, the hourly temperature variation on TGBR surface was warmer than for 4 cm depth, approximately the same as for 6 cm depth, and colder than for 8 cm depth by almost 1°C . For EGR16, the hourly temperature variation at the depth of 16 cm depth was lower than at 6 and 11 cm depths, and higher than on TGBR surface; this difference might be due to the sensor location. Under EGR8 and EGR16 substrates, the hourly temperature variation was slightly higher at TGBR surface and notably greater at 11 cm depth.

Although temperature values deviated from comfort level (18°C for cold days), the heat storage effect of VRs was clearly illustrated and temperature fluctuations did not affect the roof membrane due to the substrate layer. Moreover, the thermal insulation properties of VRs in cold days could be improved by increasing the substrate depth or the thickness of the thermal insulation layer. The values in **Figure 4-9** were slightly lower than the ones recorded by Bass and Baskaran (2003) in Canada, where the temperature fluctuated by 25°C for a traditional roof membrane and by 4°C for a vegetative roof membrane on typical winter days without snow coverage [51].

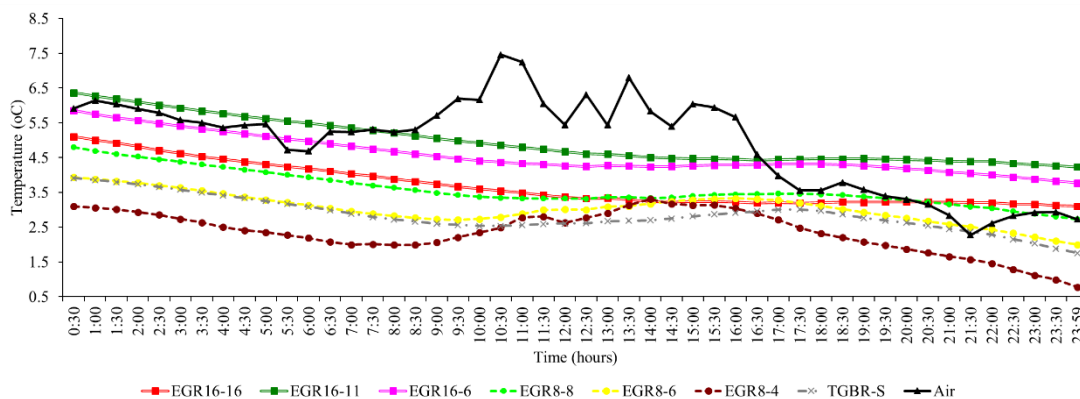


Figure 4-9: Temperature measurements on a cold winter day (25 Jan 2016)

4.4.3.2 Typical sunny winter day

The temperature at different substrate depths, on TGBR surface, and in the air during a typical sunny winter day was recorded and displayed in **Figure 4-10**. The temperature amplitudes of air and on the surfaces of TGBR, EGR8, and EGR16 were 17.77°C , 9.98°C , 8.76°C , and 17.93°C , respectively. Moreover, the surface temperature increased between 8:00 and 13:30 because the rooftop surfaces were heated up by the sun rays and then decreased during the rest of the day. This temperature fluctuation was less noticeable under the substrate (7.60°C for

EGR8 substrate and 5.77°C for EGR16 substrate). As a result, the base roof membrane was protected from extensive temperature fluctuations which may cause serious damage if frequently occurring [13, 14].

From another perspective, temperature values below EGR8 and EGR16 substrates were colder than air and on TGBR surface and were very close to comfort level (21°C during hot days). For instance, the highest air and TGBR surface temperatures were 32.57°C and 25.58°C compared to approximately 21.00°C at the depth of 8 and 16 cm for EGR8 and EGR16, respectively. Subsequently, the substrate layer of EGR8 and EGR16 reduces the air temperature by a factor of one and a half. Unexpectedly, the passive cooling effect was noticeable even in typical sunny winter days ($T_{air\ max} = 32^{\circ}C$). The findings in this study were in agreement with the work of Bass and Baskaran (2003) and Teemusk and Mander (2009) [51, 52].

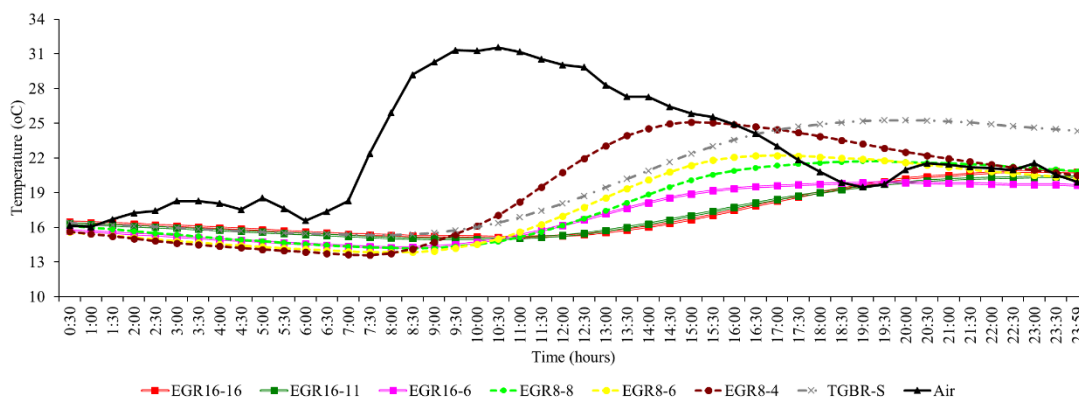


Figure 4-10: Temperatures on a sunny winter day (13 Mar 2016)

4.5 Economic study

4.5.1 Degree Days (DD)

HDDs and CDDs were calculated based on daily average temperatures. The outside temperature (T_A) for EGR16, EGR8, and TGBR was calculated based on the temperatures provided by the thermocouples labeled EGR16-th, EGR8-th, and TGBR-th respectively. Moreover, the heat lost/gain through exterior doors, windows, and walls were not taken into consideration in this study. In addition, the costs associated to heating and cooling were computed for a residential house of medium size (200m²) to reach comfortable temperature conditions. **Table 4-2** indicates the monthly HDD and CDD, with the estimated cost in US\$ for the three roofs mockups.

The total HDD and CDD of TGBR were, greater by 6.72 and 56.20 than for EGR8 and EGR16, respectively. As a result, during the winter season, EGR8 and EGR16 could result in savings of 1.39 US\$ and 11.61 US\$, respectively, when compared to TGBR.

Table 4-2: HDD, CDD, and energy cost on a monthly basis for TGBR, EGR8, and EGR16 mockups

		January 2016	February 2016	March 2016	Total	
TGBR	HDD	177.24	114.90	76.72	368.86	375.58
	CDD	0.00	0.00	6.72	6.72	
	E _{HDD}	\$36.60	\$23.73	\$15.84	\$76.17	\$77.56
	E _{CDD}	\$0.00	\$0.00	\$1.39	\$1.39	
EGR8	HDD	164.75	127.35	76.47	368.57	368.86
	CDD	0.00	0.00	0.29	0.29	
	E _{HDD}	\$34.02	\$26.30	\$15.79	\$76.11	\$76.17
	E _{CDD}	\$0.00	\$0.00	\$0.06	\$0.06	
EGR16	HDD	133.10	116.65	68.94	318.69	319.38
	CDD	0.00	0.00	0.70	0.70	
	E _{HDD}	\$27.48	\$24.09	\$14.24	\$65.81	\$65.95
	E _{CDD}	\$0.00	\$0.00	\$0.14	\$0.14	

4.5.2 Installation cost of 1m² of TGBR, EGR8, and EGR16

The lifetime of TGBR was assumed to be 15 years while the lifespan of VRs was considered as 45 years [18]. Therefore, to fulfil a lifetime criteria of 45 years, 3 TGBR and 1 EGR are needed. The amount and cost of the different layers were calculated and displayed in **Table 4-3**. For 45 years, 1m² of TGBR costs 115.17 US\$, while 1m² of EGR8 and EGR16 costs 66.02 US\$ and 70.36 US\$, respectively.

Table 4-3: Amount and cost (US\$) of materials for 1m² of TGBR, EGR8, and EGR16 for 45 years

		Amount			Cost (US\$)		
		TGBR	EGR8	EGR16	TGBR	EGR8	EGR16
Roof Assembly	Bricks		4.73 bricks		8.52		2.84
	Steel		13.50 kg		15.19		5.06
	Concrete		0.20 m ³		40.71		13.57
	Thermal insulation		1 m ²		18.75		6.25
	waterproof membrane		1 m ²		13.5		4.50
	Root barrier	---- ^a		1 m ²	----		9.35
	Drainage layer	---- ^a		1 m ²	----		17.76
	Filter sheet		1 m ²		3.00		1.00
Substrate	Soil	---- ^a	0.04 m ³	0.09 m ³	----	0.23	0.46
	Peat	---- ^a	29.60 L	59.20 L	----	4.07	8.14
	Fertilizer	---- ^a	0.04 kg	0.09 kg	----	0.04	0.08
	Plants	---- ^a		1 m ²	----		0.25
	Pebbles	0.10 m ³		---- ^a	10.00	----	
Assembly & disassembly		5		1	5.50		1.10
TOTAL					115.17	66.02	70.36
					US\$	US\$	US\$

a: Material not needed for the particular roof.

4.5.3 Cost savings for 1 month

This section elaborates the monthly money savings, based on the total cost of each type of roofs for 45 years. Fioretti et al. (2010) [15] showed that EGRs, generally, do not require maintenance therefore in this study the maintenance cost for EGR was assumed to be 0.25 US\$/m²/month less than that of TGBR no matter what the initial maintenance cost is. The cost of 1m² of TGBR, EGR8, and EGR16 as well as the heating and cooling costs are presented in **Table 4-4**. The construction cost for 45 years of 1m² of VR was 39% less than the cost of 1 m² of TGBR for the same period. However, after considering the thermal benefit of VRs for 45 years, the expenses of 1 m² were 66% less than that of TGBR.

The total cost (construction, maintenance, and energy) of 200 m² TGBR, EGR8, and EGR16 roofing systems for 45 years was 36,994 US\$, 13,415 US\$, and 12,444 US\$ respectively. As a result, in the Lebanese climate, an EGR could contribute to monthly money savings of up to 45.46 US\$.

Table 4-4: Money savings for EGR8 and EGR16 compared to TGBR

	TGBR (US\$)	EGR8 (US\$)	EGR16 (US\$)
Total roof cost/1m ² /45years	115.17	66.02	70.36
Total roof cost/200m ² /45years	23,033.90	13,204.39	14,071.98
Energy cost/200m ² /3months	77.56	76.17	65.95
Energy cost/200m ² /45years	13,960.38	13,710.45	11,871.46
Reduction in maintenance cost/1m ² /month	0.00	-0.25	-0.25
Reduction in maintenance cost/200m ² /month	0.00	-50.00	-50.00
Reduction in maintenance cost/200m ² /45years	0.00	-13,500.00	-13,500.00
<u>Total cost/200m²/45years</u>	<u>36,994.28</u>	<u>13,414.8</u>	<u>12,443.44</u>
Total cost/200m ² /1year	822.10	298.11	276.52
Total cost/200m ² /1month	68.51	24.84	23.04
Saving/200m ² /1month	-43.67	-45.46	

4.6 Conclusion

Results of this paper confirmed that VRs protect the roof membrane from high temperature fluctuations. This protection is ensured due to many thermal phenomena such as evapotranspiration, thermal resistance, and solar shading. Thus, VRs increase the life time of the base roof membrane.

During a sunny winter day (March 13, 2016), VRs verify the passive cooling effect by decreasing air temperature by a factor of one and a half. This aspect makes VRs an effective solution for enhancing the thermal comfort and reducing the cooling demand. In parallel, VRs seem to be advantageous even in the winter season for the Lebanese climate, which has relatively moderate temperatures compared to Europe or North America. During the winter season, the total HDD of EGR16 was 15% less than the total HDD of the TGBR but the total CDD of EGR16 was 90% less than that of the TGBR. Therefore, the installation of VRs in a country like Lebanon could not only improve the aesthetic looks of buildings, but also help reduce the energy deficit all year round.

From another perspective, VRs highly affect the heating/cooling demand of a residential building in the Lebanese climate leading to a monthly money saving of up to 45 US\$/200m².

Further work would target water retention performance of VRs, water runoff quality of VRs, and air quality and biodiversity of VRs in Mediterranean climate zones. A full cradle to grave Life Cycle Assessment of vegetative roofs might also give other insights.

4.7 Acknowledgement

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4.8 References

- [1] Nowak, D. J., Civerolo, K. L., Trivikrama Rao, S., Gopal Sistla, Luley, C. J., & E. Crane, D. (2000). A modeling study of the impact of urban trees on ozone. *Atmospheric Environment*, 34(10), 1601-1613. doi: [http://dx.doi.org/10.1016/S1352-2310\(99\)00394-5](http://dx.doi.org/10.1016/S1352-2310(99)00394-5).
- [2] Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in chicago. *Atmospheric Environment*, 42(31), 7266-7273. doi: <http://dx.doi.org/10.1016/j.atmosenv.2008.07.003>.
- [3] Li, J., Wai, O. W. H., Li, Y. S., Zhan, J., Ho, Y. A., Li, J., & Lam, E. (2010). Effect of green roof on ambient CO₂ concentration. *Building and Environment*, 45(12), 2644-2651. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.05.025>.
- [4] Wilmers, F. (1990). Effects of vegetation on urban climate and buildings. *Energy and Buildings*, 15(3), 507-514. doi: [http://dx.doi.org/10.1016/0378-7788\(90\)90028-H](http://dx.doi.org/10.1016/0378-7788(90)90028-H).
- [5] Sailor, D.J., 2004. "Ecoroofs and the Urban Climate", presented at the Second Annual Greening Rooftops for Sustainable Communities Conference, Portland, OR, June 2-4.
- [6] Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, 43(4), 480-493. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.10.055>.
- [7] Wong, N. H., Chen, Y., Ong, C. L., & Sia, A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, 38(2), 261-270. doi: [http://dx.doi.org/10.1016/S0360-1323\(02\)00066-5](http://dx.doi.org/10.1016/S0360-1323(02)00066-5).
- [8] Takebayashi, H., & Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment*, 42(8), 2971-2979. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.06.017>.

- [9] Gomez, F., Gaja, E., & Reig, A. (1998). Vegetation and climatic changes in a city. *Ecological Engineering*, 10(4), 355-360. doi: [http://dx.doi.org/10.1016/S0925-8574\(98\)00002-0](http://dx.doi.org/10.1016/S0925-8574(98)00002-0).
- [10] Peck SW, Callaghan C, Kuhn ME, Bass B. (1999). Greenbacks from Green Roofs: Forging a New Industry in Canada. <http://www.w.carmelacanzonieri.com/3740/readings/greenroofs%2Bgreen%20design/Greenbacks%20from%20greenroofs.pdf>. Accessed on March 1, 2016.
- [11] Wong, N. H., Cheong, D. K. W., Yan, H., Soh, J., Ong, C. L., & Sia, A. (2003). The effects of rooftop garden on energy consumption of a commercial building in singapore. *Energy and Buildings*, 35(4), 353-364. doi: [http://dx.doi.org/10.1016/S0378-7788\(02\)00108-1](http://dx.doi.org/10.1016/S0378-7788(02)00108-1).
- [12] Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in athens, greece. *Energy*, 32(9), 1781-1788. doi: <http://dx.doi.org/10.1016/j.energy.2006.11.011>.
- [13] Djedjig, R., Bozonnet, E., & Belarbi, R. (2013) Integration of a green envelope model in a transient building simulation program and experimental comparison. 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28. 47-53.
- [14] Teemusk, A., & Mander, Ü. (2010). Temperature regime of planted roofs compared with conventional roofing systems. *Ecological Engineering*, 36(1), 91-95. doi: <http://dx.doi.org/10.1016/j.ecoleng.2009.09.009>.
- [15] Fioretti, R., Palla, A., Lanza, L. G., & Principi, P. (2010). Green roof energy and water related performance in the mediterranean climate. *Building and Environment*, 45(8), 1890-1904. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.03.001>.
- [16] Lin, Y., & Lin, H. (2011). Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. *Building and Environment*, 46(2), 345-355. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.07.027>.
- [17] Onmura, S., Matsumoto, M., & Hokoi, S. (2001). Study on evaporative cooling effect of roof lawn gardens. *Energy and Buildings*, 33(7), 653-666. doi: [http://dx.doi.org/10.1016/S0378-7788\(00\)00134-1](http://dx.doi.org/10.1016/S0378-7788(00)00134-1).

- [18] Kosareo, L., & Ries, R. (2007). Comparative environmental life cycle assessment of green roofs. *Building and Environment*, 42(7), 2606-2613. doi: <http://dx.doi.org/10.1016/j.buildenv.2006.06.019>.
- [19] Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and Environment*, 46(3), 729-738. doi: <http://dx.doi.org/10.1016/j.buildenv.2010.10.006>.
- [20] Brenneisen, S. The benefits of biodiversity from green roofs-key design consequences. 1st North American green roof conference: greening rooftops for sustainable communities. Chicago, IL: The Cardinal Group, Toronto; 2003. 323–329.
- [21] Koehler, M. (2004). Ecological green roofs in Germany. *Journal of the Korea Society for Environmental Restoration and Revegetation Technology*. 7(4), 8-16.
- [22] Jörg, B. (2013). The economics of green roofs from the perspective of the commercial client. Retrieved from <http://www.greenrooftechnology.com/green-roof-blog/the-economics-of-green-roofs-from-the-perspective-of-the-commercial-client>.
- [23] C.Y. Jim, S.W. Tsang, Ecological energetics of tropical intensive green roof, *Energy Build.* 43 (10) (2011) 2696-2704.
- [24] E. Oberndorfer, J. Lundholm, B. Bass, R.R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K.K.Y. Liu, B. Rowe, Green roofs as urban ecosystems: ecological structures, functions, and services, *BioScience* 7 (10) (2007) 823-833.
- [25] Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, 42(10), 1582-1591. doi: <http://dx.doi.org/10.1016/j.enbuild.2010.05.004>.
- [26] Jaffal, I., Ouldboukhite, S., & Belarbi, R. (2012). A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy*, 43, 157-164. doi: <http://dx.doi.org/10.1016/j.renene.2011.12.004>.
- [27] Lazzarin, R. M., Castellotti, F., & Busato, F. (2005). Experimental measurements and numerical modelling of a green roof. *Energy and Buildings*, 37(12), 1260-1267. doi: <http://dx.doi.org/10.1016/j.enbuild.2005.02.001>.
- [28] Antonio Gagliano, A.; Detommaso, M.; olera, F.; and Evola, G. 2015. A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and

- traditional roofs. *Building and Environment* 90, 71-81.
<http://dx.doi.org/10.1016/j.buildenv.2015.02.043>.
- [29] Yaghoobian.N, Kleissl.J. (2012). Effect of reflective pavements on building energy use. *Urban Climate* 2 (2012) 25–42. <http://dx.doi.org/10.1016/j.uclim.2012.09.002>.
- [30] Castleton, H.F.; Stovin, V.; Beck, S.B.M.; Davison, J.B.. 2010. Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings* 42, 1582–1591. doi: [10.1016/j.enbuild.2010.05.004](http://dx.doi.org/10.1016/j.enbuild.2010.05.004).
- [31] Jim, C.Y; Tsang, S.W.. 2011. Biophysical properties and thermal performance of an intensive green roof. *Building and Environment* 46, 1263-1274. doi:[10.1016/j.buildenv.2010.12.013](http://dx.doi.org/10.1016/j.buildenv.2010.12.013).
- [32] Theodosiou, T-G. 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. *Energy and Buildings* 35, 909–917. doi: [10.1016/S0378-7788\(03\)00023-9](http://dx.doi.org/10.1016/S0378-7788(03)00023-9).
- [33] Fardoun, F., Ibrahim, O., Younes, R., & Louahlia-Gualous, H. (2012). Electricity of Lebanon: Problems and recommendations. *Energy Procedia*, 19, 310-320. doi: <http://dx.doi.org/10.1016/j.egypro.2012.05.211>.
- [34] The World Bank. (2010). *Republic of Lebanon - water sector: Public expenditure review*. (Public Expenditure Review No. 52024-LB).The World Bank.
- [35] Akkaya, S., Junge, N., & Mansour, W. (November 2009). *LEBANON: Social impact analysis for the electricity and water sectors*. (No. 51803-LB).The World Bank.
- [36] The European Union. (2012). *Paving the way for the Mediterranean solar plan: Lebanon*. (No. ENPI 2010/248-486).The European Union.
- [37] Knack, S., & Eubank, N. (June 18, 2009). *Lebanon social impact analysis - electricity and water sectors*. (Policy Note No. 48993-LB). The World Bank.
- [38] Hao, Y., Chen, H., Wei, Y., & Li, Y.The influence of climate change on CO₂ (carbon dioxide) emissions: An empirical estimation based on chinese provincial panel data. *Journal of Cleaner Production*, doi: <http://dx.doi.org/10.1016/j.jclepro.2016.04.117>.
- [39] Bjerde, A., Covindassamy, A., Hamaide, M., Takahashi, M., & Araujo, A. (January 31, 2008). *Republic of Lebanon electricity sector public expenditure review*. (Public Expenditure Review No. 41421-LB). The World Bank.

- [40] El Bachawati, M., Manneh, R., Belarbi, R., Dandres, T., Nassab, C., & El Zakhem, H. (2016). Cradle-to-gate Life Cycle Assessment of traditional gravel ballasted, white reflective, and vegetative roofs: A Lebanese case study. *Journal of Cleaner Production*, 137, 833-842. Doi: <http://dx.doi.org/10.1016/j.jclepro.2016.07.170>.
- [41] Green roof components. Retrieved from <http://zinco.ca/planning.html>. Accessed on April 15, 2016.
- [42] MESUREX. Capteur thermocouple. Retrieved from http://www.mesurex.fr/fiche-a02capteur_thermocouple_++de+la+marque-26.html. Accessed on April 15, 2016.
- [43] CAMPBELL SCIENTIFIC. (2016). CR1000 measurement and control system. Retrieved from <https://www.campbellsci.com/cr1000>. Accessed on April 15, 2016.
- [44] CAMPBELL SCIENTIFIC. (2016). 16-channel or 32-channel relay multiplexer. Retrieved from <https://www.campbellsci.com/am16-32>. Accessed on April 15, 2016.
- [45] Tinytag. (2016). Rugged, waterproof temperature and relative humidity logger with built-in sensors. Retrieved from <http://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4500>. Accessed on April 15, 2016.
- [46] Martin, B. (2009). Degree days. Retrieved from http://www.degree-days.net/introduction#Heating_degree_days.
- [47] The Weather Company, L. (2016). Heating degree days and cooling degree days. Retrieved from <https://www.wunderground.com/about/faq/degreedays.asp?MR=1>. Accessed on April 15, 2016.
- [48] Électricité Du Liban. (2015). Électricité du Liban (EDL). Retrieved from <http://www.edl.gov.lb>. Accessed on March 14, 2016.
- [49] He, Y., Yu, H., & Zhao, M. (2015). Thermal performance study of extensive green roof in Shanghai district: A case study of lightweight building in winter. *Procedia Engineering*, 121, 1597-1604. doi: <http://dx.doi.org/10.1016/j.proeng.2015.09.186>.
- [50] Theodosiou, T. G. (2003). Summer period analysis of the performance of a planted roof as a passive cooling technique. *Energy and Buildings*, 35(9), 909-917. doi: [http://dx.doi.org/10.1016/S0378-7788\(03\)00023-9](http://dx.doi.org/10.1016/S0378-7788(03)00023-9).
- [51] Bass B, Baskaran B. Evaluating rooftop and vertical gardens as an adaptation strategy for urban areas. Institute for Research and Construction, NRCC- 46737, Project No. A020,

CCAF Report B1046. Ottawa, Canada: National Research Council, 2003 .p.110
[/http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc46737/nrcc46737.pdf](http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc46737/nrcc46737.pdf)S.

- [52] Teemusk, A., & Mander, Ü. (2009). Green roof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia. *Building and Environment*, 44(3), 643-650. doi: <http://dx.doi.org/10.1016/j.buildenv.2008.05.011>.

CHAPTER 5 PERFORMANCE OF EXTENSIVE GREEN ROOFS TOWARDS RUNOFF WATER QUANTITY AND QUALITY: A LEBANESE CASE STUDY

5.1 Abstract

Stormwater management and runoff dynamics of a Traditional Gravel Ballasted Roof (TGBR) and two Extensive Vegetated Roofs (EGRs) that differ in their substrate depth and composition are experimentally assessed. The stormwater management was evaluated through a real-time soil moisture monitoring in the Lebanese winter season, while the runoff water quality was determined by measuring pH values, nutrients, and heavy metals loads in samples of rain water and runoff water from TGBR and EGRs. Results showed that the studied EGRs effectively delayed the runoff and highly retained rain events compared to TGBR. Also, the quality of runoff water was dependent on the growth medium composition, delay, and intensity of rainfall. EGRs highly reduced the load of nutrients and heavy metals in runoff water.

5.2 Introduction

Vegetative roofs (VRs), referred to as living roofs, are systems that foster the growth of plants on roofs [1]. These roofs have often been assessed to explore their stormwater management and runoff water dynamics in comparison with Traditional Gravel Ballasted Roofs (TGBRs) especially in urban areas. TGBRs are made of the following layers: concrete membrane (hollow concrete blocks, rebar, and concrete), thermal insulation layer, waterproof membrane, filter sheet, and pebbles as an exterior layer. VRs are assembled using the following layers: concrete membrane (same as for TGBRs), thermal insulation layer, waterproof membrane, root resistant barrier, drainage layer, filter sheet, growing medium, and vegetation [2]. There are mainly two types of VRs: extensive and intensive [3]. Extensive Green Roofs (EGRs) are characterized by a thin substrate layer (between 10 and 15cm), while Intensive Green Roofs (IGRs) are characterized by a thicker substrate layer (between 20 and 100cm) [4].

Over the last few years, VRs were better appreciated due their numerous benefits compared to TGBRs. VRs could be a possible solution to many environmental and health problems such as: runoff water which raises road flooding [5], high air temperatures [6], poor air quality [7], low wildlife habitat [8], and low biodiversity [9]. Also, VRs present some economic and ecological advantages such as noise reduction [10] and increase of the longevity of the base roof

membrane [11]. VRs also have thermal benefits especially during summertime such as the following: reduction of temperature fluctuation [12], conservation of energy [13], mitigation of Urban Heat Island (UHI) magnitude [14] and energy consumption [15], and reduction of rooftop temperature [16]. Moreover, VRs are more aesthetic than TGBRs [17].

Although VRs are gaining more and more popularity due to many environmental, economical, and thermal benefits, the quality of runoff water is not well highlighted. To date, only very few studies explored stormwater management and runoff dynamics of VRs compared to TGBRs [18, 19]. In particular, the drainage and substrate layers hold stormwater, leading to the alternation of the magnitude and the timing of peak runoff. This is particularly important in cities where sewage and stormwater systems are combined [20]. Fioretti *et al.* (2010) [21] studied the energy and water performances of VRs stating that for a Mediterranean climate, VRs significantly mitigate runoff water volume and attenuate runoff water peak. Besides, Villarreal and Bengtsson (2005) explored the response of sedum vegetative roofs to individual rain events in Lund (Sweden) finding that with dry substrate, water was retained and detained, whereas with wet substrate, water was only detained. Villarreal and Bengtsson (2005) revealed that with dry substrate and uniform rain intensity, 6 to 12 mm of rain were necessary to initiate runoff [40]. Nawaz *et al.* (2015) [23] studied the water performance of EGRs located in a moderate climate and found that EGRs were capable to detain 66% of rainfall water and attenuate runoff peaks compared to TGBRs. However, this retention was reduced for larger rainfall events due to the limited retention capacity of the EGRs.

The installation and use of VRs is still very rare in Lebanon, with only two EGRs to date. This Mediterranean country lacks a clear sustainable plan and suffers from major problems in the water and electricity sectors since the civil war (1975-1990) despite the existence of a major rehabilitation plan [24, 25]. Although the installation of VRs is viewed as a management practice to attenuate peak runoff in urban areas [26] and improve stormwater quality [27], there are several barriers to the widespread adoption of this technology.

The originality of this research also lies in the constitution of the VRs' media. While the environmental benefits of VRs are well understood, the scientific understanding of this technology is still in its earliest stages in Lebanon. This work, first of its kind in Lebanon, aims to i) characterize and analyze the water management of two EGR mockups distinguished by their media depth and composition to a TGBR mockup in winter season and ii) determine the runoff water quality and quantity.

5.3 Material and methods

5.3.1 Mockups description: Experimental bench

Three roof mockups were set up on the rooftop of the Chemical Engineering Department at the University of Balamand, Lebanon (34.36°N, 35.78°E) in December 2015. These mockups consist of one TGBR and two EGRs with different composition and substrate depth “EGR8” and “EGR16” (8 and 16 cm, substrate depth respectively) (**Figure 5-1**). **Table 5-1** represents the amounts of materials constituting each mockup. In fact, hollow concrete blocks, rebar, concrete, thermal insulation boards, waterproof membrane, and filter sheet were supplied from local suppliers. For the pebbles, plants, and the components of the growing medium, they were provided by the landscaping, gardening and agriculture department at the University of Balamand. As for the anti-root and the drainage layers, they were delivered from Zinco, Germany.



Figure 5-1: Mockups at the roof of the Chemical Engineering building: (a) TGBR (b) EGR8 (c) EGR16

Table 5-1: Components of the TGBR, EGR8, and EGR16 mockups

	TGBR	EGR 8	EGR16
	1 Brick	1 Brick	1 Brick
Roof assembly	Steel: 6.61 kg Concrete: 308.75 kg	Steel: 6.61 kg Concrete: 308.75 kg	Steel: 6.61 kg Concrete: 308.75 kg
Thermal insulation	Styrofoam: 0.5 m ²	Styrofoam: 0.5 m ²	Styrofoam: 0.5 m ²
Waterproof	SBS waterproof	SBS waterproof	SBS waterproof
Root resistant barrier	N.D.	ZinCo WSF 40	ZinCo WSF 40
Drainage	N.D.	ZinCo FD 40-E	ZinCo FD 40-E
Filter	ZinCo SF	ZinCo SF	ZinCo SF
Growing medium	N.D.	Soil: 11.20 kg	Soil: 25.60 kg
		Peat: 21.45 kg	Peat: 41.25 kg
		Alumina: 28.80 kg	Alumina: 0.00 kg
		Pumice: 5.13 kg	Pumice: 19.87 kg
		Fertilizer: 0.07 kg	Fertilizer: 0.15 kg
Vegetation	N.D.	<i>Rosemary</i>	<i>Rosemary</i>
		<i>Lavender</i>	<i>Lavender</i>
		<i>Alyssum</i>	<i>Alyssum</i>
		<i>Argyranthemum</i>	<i>Argyranthemum</i>
		<i>madeira</i>	<i>madeira</i>
		<i>Marguerite daisy</i>	<i>Marguerite daisy</i>
		<i>Gazania rigens</i>	<i>Gazania rigens</i>
		<i>Lobularia maritima</i>	<i>Lobularia maritima</i>
Pebbles	10 cm	N.D.	N.D.

N.D.: Component not needed for the particular roof mockup.

Mockups were uncovered, spaced 40 cm from each other with an individual area of 0.5 m², and assembled about 10 m above ground level. While TGBR and EGR8 mockups were leveled, EGR16 had a slope of 6%. During the measurement period (January 14th until March 31st 2016), the plants covered around 45% of the roof surface for both EGR8 and EGR16 as the weather conditions prevented a further development of plants.

5.3.2 Sensors installation and measurements

The internal moisture of TGBR, EGR8, and EGR16 roof mockups was measured using twelve soil moisture sensors from Decagon devices (United States) [28], recorded with a CR1000 measurement and control datalogger connected to an AM 16/32B channel relay multiplexer produced by Campbell Scientific (United States) [29, 30], and read through a 32-bit desk top computer. The relative humidity (RH) of the air was monitored using a waterproof relative humidity sensor ordered from Gemini Data Loggers (United Kingdom) [31] and read with Tinytag explorer 4.9. Moisture measurements were recorded every minute. Air RH was measured at 5 and 110 cm height above the surface of TGBR mockup. **Figure 5-2** depicts the location of the soil moisture probes and the RH sensors in/above TGBR, EGR8, and EGR16 mockups. For TGBR (**Figure 5-2.a**), two soil moisture sensors were used, the first between the thermal insulation layer and the waterproof membrane, and the second between the filter sheet and the pebbles layer. For EGR8 (**Figure 5-2.b**), five soil moisture probes were installed, the first one between the thermal insulation layer and the waterproof membrane, and the others at the depths of 2, 4, 6, and 8 cm of the substrate layer. Similarly, for EGR16 (**Figure 5-2.c**), five soil moisture probes were installed, the first between the thermal insulation layer and waterproof membrane, and the rest at 1, 6, 11, and 16 cm of the substrate depths.

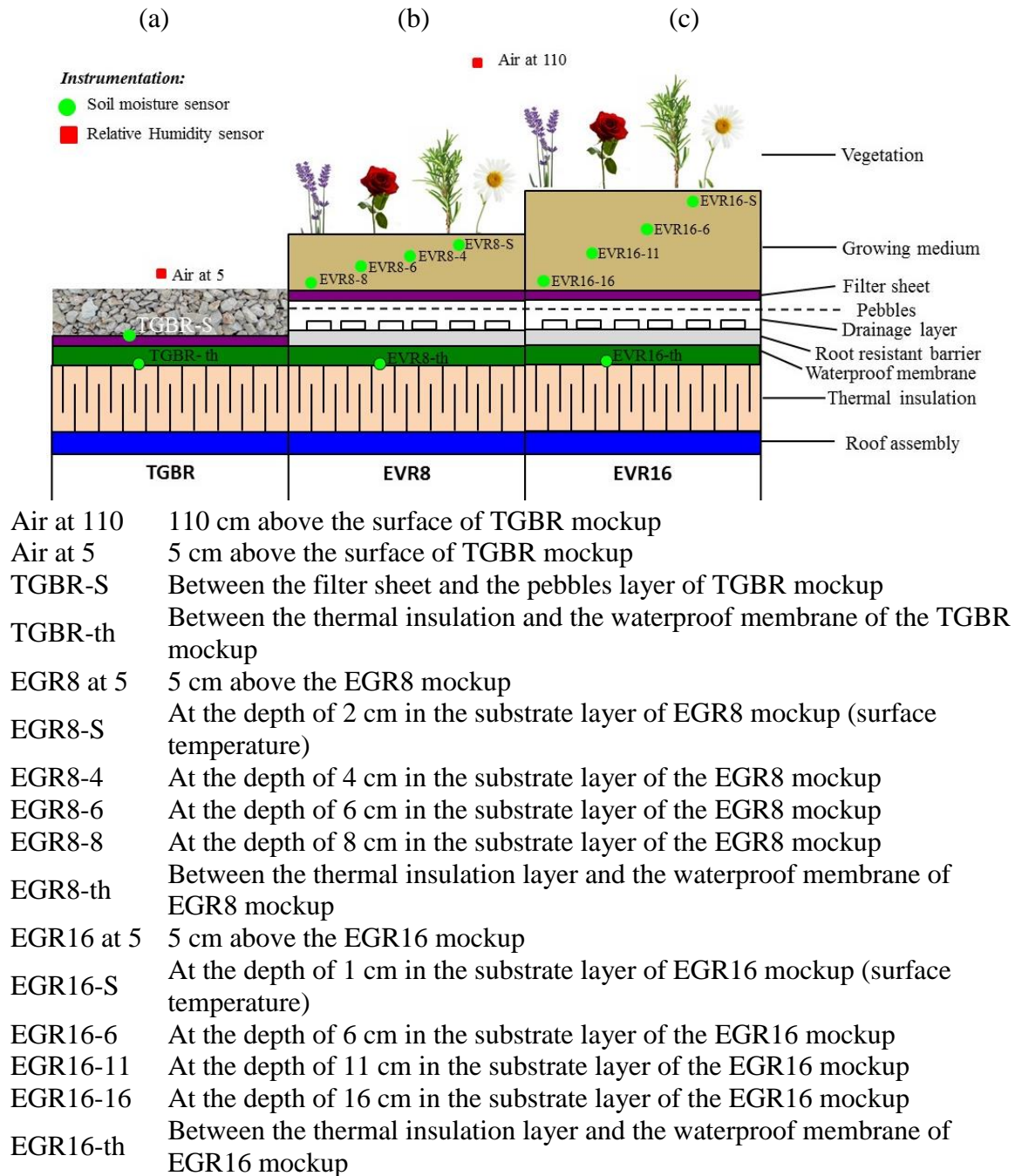


Figure 5-2: Moisture sensors location for: (a) TGBR (b) EGR8 and (c) EGR16 mockups

In addition to soil moisture and RH sensors, three rain water gauges were mounted on each roof mockup. An additional water gauge was used to measure the amount of rainfall. Rain water gauges were connected to screens displaying the number of tips. Each tip is equivalent to 0.01 in. of rainfall. From this, runoff volume, rainfall duration, runoff time, delay between runoffs, and duration between 2 precipitations were calculated. Also, runoff water from each mockup and rainfall water were collected and analyzed.

5.3.3 Runoff water quality procedure

250 mL of runoff water and rain water were collected in glass bottles with a polyethylene cover. Prior to sampling, glass bottles were rinsed multiple times with demineralized water. In total seven color comparator tests (AQUANAL-plus) were carried out to quantify the following nutrients and heavy metals: cadmium (Cd), ammonium nitrogen (NH_4), copper (Cu), chromium (Cr), iron (Fe), Total-hardness (calcium: Ca), and zinc (Zn) [32]. For all tested, a certain volume of water sample was poured to a glass tube, then the needed reagents were added, dissolved by shaking, and left to stand for few minutes. The last step is the color comparison between the test tube and the color comparator chart. Method and detection ranges are represented in **Table 5-2**. Furthermore, pH tests were done using a benchtop meter (pH meter inoLab pH 7110) [33].

Table 5-2: Color comparator tests

	Measuring range	Method
Cd	0.02-1.25 mg/L Cd	Formation of a yellow- red color complex
Cu	0.05-0.5 mg/L Cu^{2+}	Formation of a blue color complex
	0.4-4.5 mg/L Cu^{2+}	
Fe	0.2-15 mg/L $\text{Fe}^{2+/3+}$	Formation of a red color complex
Cr	0.005-0.1 mg/L Cr^{2+}	Formation of a red-violet dye
Zn	0.1-5 mg/L Zn^{2+}	Formation of a green color complex
NH_4^+	0.2-8 mg/L NH_4^+	Formation of blue color
Ca	1 drop=1°d (0.178mmol/L Ca)	Variation of color from red to green

5.4 Results and discussion

5.4.1 Relative Humidity of air and water content of EGRs

The average daily air relative humidity was measured at a height of 5 and 110 cm and compared to the daily average Volumetric Water Content (VWC) under the EGR8 and EGR16 substrates (at a depth of 8 and 16 cm) (**Figure 5-3**). The Water Content (WC), i.e. the amount of water enclosed in soil, is expressed as a ratio which can range from 0 (completely dry) to 1 (completely saturated). It could be given on a volumetric (% of volume) or a gravimetric (% of weight) basis. Results indicated a significant difference between the water vapor in the air and

the Volumetric Water Content at the bottom of the substrate layer. Thus, EGRs highly reduced the stormwater runoff during winter season. The values of runoff reduction cannot be easily compared to reviewed studies due to different meteorological conditions in which studies were performed including the duration of the study, intensity of the rainfall, and number of rainfalls considered to calculate retention values. For instance, the studies done in Germany between 1987 and 2003 and summarized by Mentens *et al.* [22] in 2006 stated that EGRs, with an average substrate depth of 10 cm, reduce the annual runoff by 45%.

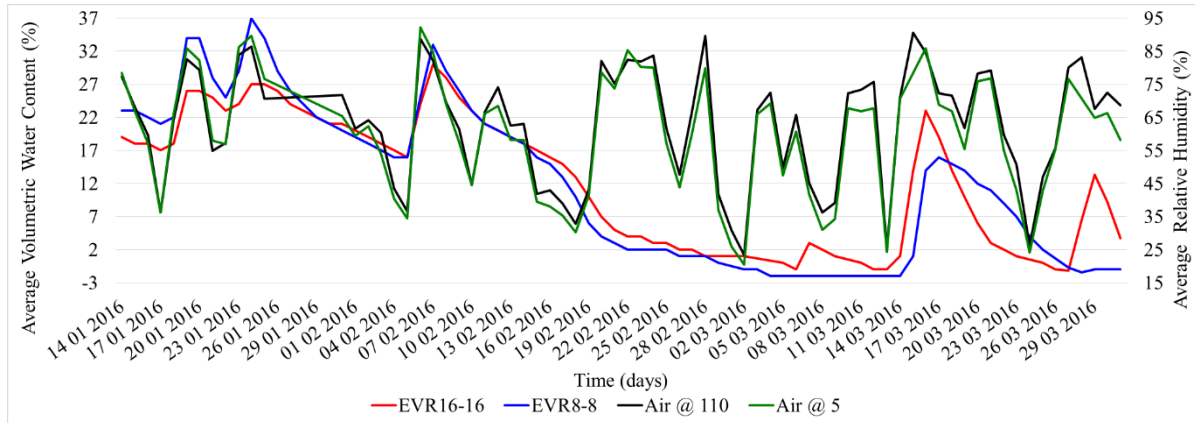


Figure 5-3: Comparison of air RH measured at 5 and 110 cm heights with WC at the depths of 8 and 16 cm

5.4.2 Volumetric Water content at different depth of EGRs

The soil moisture was measured at 4, 6, and 8 cm below EGR8 surface and at 6, 11, and 16 cm below EGR16 surface. Soil moisture variations for a typical rainy and cold winter day (total precipitation of 36.58mm and air temperature below 2.5°C, e.g. January 25, 2016) and for a sunny and hot winter day (sunshine for 11.88 hours and air temperature above 32°C, e.g. March 13, 2016) are represented in **Figure 5-4** for both EGR8 and EGR16 while daily soil moisture variations are displayed in **Figures 5-5** and **5-6**. In typical days, for both EGR8 and EGR16, soil moisture variations at different substrate depths were similar for a sunny hot day but differed for a colder rainy day. In particular, the average variations in a typical cold rainy day at the depth of 4, 6, and 8 cm was 37.76%, 40.35%, and 33.85%, respectively, for EGR8. For EGR16, average soil moisture variations for a cold and rainy day at the depth of 6, 11, and 16 cm was 23.70%, 29.05%, and 27.07%, respectively.

In addition, for both EGR8 and EGR16, the VWC between the thermal insulation layer and the waterproof membrane was not considered. In particular, soil moisture sensors were calibrated and expected to be used in growth mediums with some dielectric components. Therefore, when

measurements were taken in very dry conditions, negative values were displayed. In contrast, when the soil is near saturation ($VWC > 90\%$), the width of the electromagnetic field diminishes and the electromagnetic field measures the sensor surface. Thus, for the used soil moisture sensors, the measurement range is up to 90% VWC.

The VWC within the two substrates was higher for all the measurement period than for the surface of the TGBR. For EGR8, the VWC on the surface was very close to that at the depth of 8 cm. The partial coverage of the plants allowed wind and solar radiations to evaporate the water from the surface while the low WC at the depth of 8 cm could be due to the large adsorption of the rainfall water before reaching the soil bottom. The majority of the water was held within the first 6 cm of the substrate. At the depth of 4 and 6 cm, the WC was approximately the same and reached 40 and 42% respectively. In fact, the WC on TGBR surface was 24% and 26% lower than the WC at the depth of 4 and 6 cm respectively. These results confirm the delay and the reduction of runoff water from EGRs compared to TGBR. Accordingly, the urban road flooding is effectively mitigated, especially for moderate climate zones such as Lebanon. In fact, water retention capacity of VRs depends on the weather. During the summer season, the evapotranspiration phenomena is higher and the water retention capacity of VRs restore faster when compared to other seasons [22, 34]. In line with this, comparing with existing literature becomes more difficult because of season duration, study period, and outside temperature. Mentens *et al.* (2006) [22], defined the warm season from May 1st until September 30th, the cold season from November 16th until March 15th, and the cool seasons from October 1st until November 15th. Mentens *et al.* (2006) also showed that there was no relationship between runoff capacity and the depth of soil during cold and cool seasons while for a warm season, each 1 cm of substrate reduces the runoff by an additional 2.5 mm. For instance, during the warm season, runoff reduction at the substrate depth of 5 cm, between 5 and 15 cm, and larger than 15 cm, was 62%, 70%, 80%, respectively. For the substrate depth between 5 and 15 cm, runoff reductions were 70% for a warm season, 33% for a cold season, and 49% for a cool season.

As for EGR16, the soil surface was characterized by a low WC when compared to other depths because of the quick evaporation process. The main difference between the VWC profiles within the EGR8 and EGR16 substrates lies at 16 cm of depth. At this depth, the WC was slightly lower than at 6 and 11 cm of depth during light and medium rain events and similar during heavy rain events (e.g. February 8, 2016 and March 18, 2016). Accordingly, the rainwater was easily diffused to the bottom of EGR16 substrate unlike the case of EGR8. This

could be explained by the slope effect on the water retention dynamics and on the drainage duration. The maximum WC was 25% at the depth of 6 cm, and 30% at 11 and 16 cm depths thus reducing the WC of TGBR surface by 10-14% due to EGR16 substrate layer. To compare this finding with the very few existing studies, Kohler (2005) [35] stated that in Germany VRs with a substrate layer between 5 and 12 cm could reduce annual precipitation by 60-79%. As well, Scholz-Barth (2001) [36] concluded that, in the United States EGR could retain 65% of rainwater on average. Although increased media depths resulted in higher retention, the benefit was not high [35, 36]. From another perspective, published studies about the effect of slope on water retention capacity of VRs had two broad findings, the first stating that water retention capacity was not correlated with the slope of the roof [37, 22] while the other suggesting that water retention capacity was correlated with the slope of the roof [38, 39, 40]. The findings of this study are coherent with the second point of view. More to the point, Getter *et al.* (2007) [38] showed that EGR retained on average 80% of total rainfall for all slopes (2%, 7%, 15%, and 25%) and rain intensities (16 light, 24 medium, and 22 heavy rain events). The retention mean value was 75% of total rainfall at the highest slope (25%) and 85% of total rainfall at the lowest slope (2%). For rain events less than 2 mm, the retention was 94% of total rainfall and 63% of total rainfall for rain events greater than 10 mm.

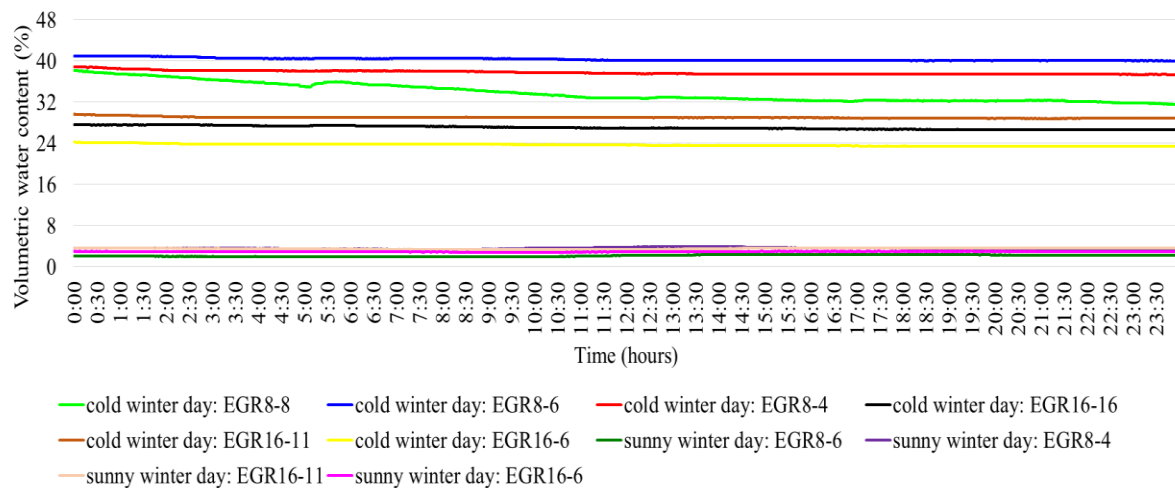


Figure 5-4: EGR8 and EGR16 soil moisture variation at three depths in cold and sunny winter days

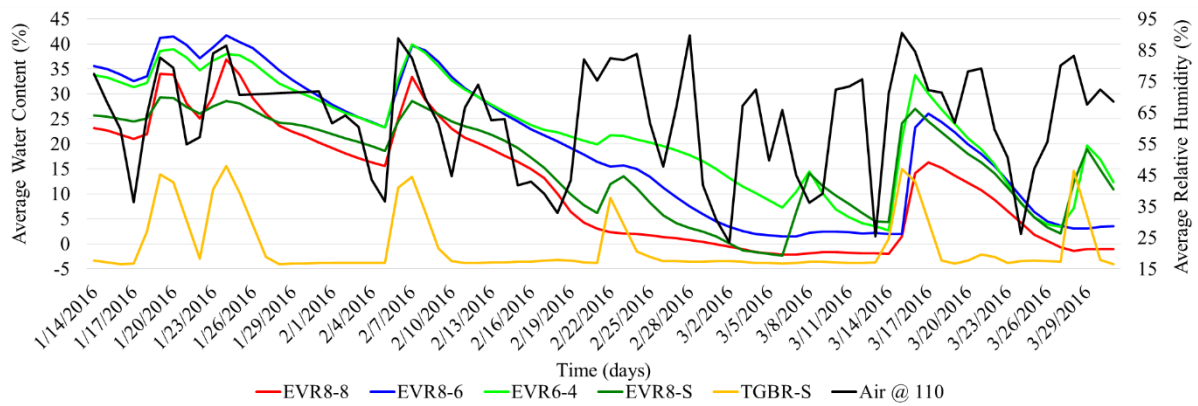


Figure 5-5: VWC monitoring through the winter period at different depths of EGR8 substrate compared to the VWC on the TGBR surface and to the RH of the air

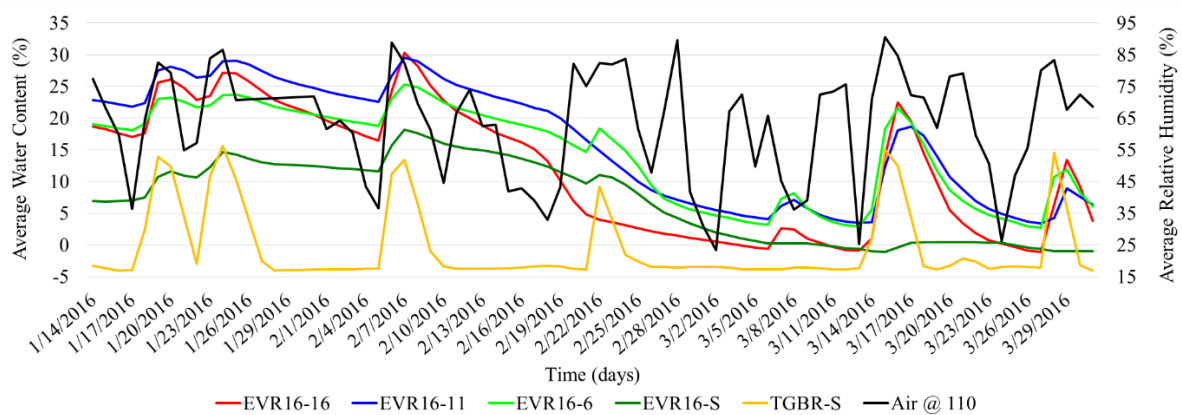


Figure 5-6: VWC at different depth of EGR16 substrate compared to the VWC on the TGBR surface and to the RH of the air

5.4.3 Delay of the runoff

The drainage and substrate layers hold the largest part of the rainfall water, leading to a reduction and delay in the runoff water from VRs compared to TGBRs. The runoff delay effect is the time lag between the peak runoff from TGBR and that from VR for the same rain event. The rainfall duration and the runoff water delay from the different studied roofs was assessed during the whole measurement period and summarized in **Table 5-3**.

On January 8, 2016, the runoff water from EGR16 was delayed 1.1 hours compared to the rainfall, 0.8 hours compared to the runoff water from TGBR, and no runoff water was observed from EGR8. In addition, the runoff water from the TGBR remained for 1.15 hours versus 0.28 hour in case of EGR16. In the same day, a second precipitation occurred. The flow time was approximately the same for the three studied roofs but EGR8 was the last to drain (0.38 hour after the first drop of rainwater). On January 18, 2016 and after the rainfall, EGR16 began to drain at 0.45 hour, TGBR at 0.7 hour, and EGR8 at 1.25 hours. Compared to the few existing

studies, Carter and Rasmussen [41] revealed that 57% of the runoff water peaks from VRs were delayed up to 10 min compared to TGBRs which coincides with the results depicted by Simmons *et al.* (2008) [42]. VanWoert *et al.* (2005) [39] also observed the same delay between media-only and VRs. In addition, DeNardo *et al.* (2005) [43] found that VRs have delayed the initiation and the peak runoff by 5.7 hours and 2 hours respectively. Similarly, significant reductions of the peak runoff were observed by Moran *et al.* (2005) [44] where the delay was half an hour for 60% of rain events. Only few studies, have compared the runoff dynamics from TGBR and EGR in the Middle East region.

Table 5-3: Examples of three rain events and drainage duration

	January 8, 2016			January 8, 2016				January 18, 2016			
	Rain event	TGBR drainage	EGR16 drainage	Rain event	TGBR drainage	EGR8 drainage	EGR16 drainage	Rain event	TGBR drainage	EGR8 drainage	EGR16 drainage
Begin	9:31	9:49	10:38	11:00	11:02	11:23	11:06	8:45	9:27	10:00	9:12
End	9:33	10:58	10:55	11:35	12:32	12:29	12:45	9:55	9:58	14:14	13:55
Duration	00:02	01:09	00:17	00:35	01:30	01:06	01:39	01:10	00:31	04:14	04:43
Delay with respect to Rain		00:18	01:07		00:02	00:23	00:06		00:42	01:15	00:27
Delay with respect to TGBR			00:49			00:21	00:04			00:33	
Delay with respect to EGR 16						00:17				00:48	

5.4.4 Relationship between the rainfall and the runoff

The relationship between rainfall and runoff profiles of TGBRs and VRs and the reduction in the drained volume has been explored (**Table 5-4**). During the entire measurement period, a total of 25 rain events occurred. The maximum single rain event and precipitation for one day were 36.32 and 36.58 mm, respectively. Furthermore, based on size and intensity, rainfalls were spread as 9 light (< 2 mm), 12 medium (< 30 mm), and 4 heavy (> 30 mm) rain events. The real time assessment showed that the weather conditions affected the water retention of EGRs. After a dry period, at least 6 mm of rain were required to initiate the runoff (January 23, 2016), while during successive rainfalls the runoff was almost straight. These observations come to confirm the outputs found by Villarreal and Bengtsson (2005) for sedum vegetative roofs in Lund (Sweden) [40] and are comparable to the findings of Bengtsson (10 mm of rain) for sedum vegetative roofs in Malmö [45].

For light rain events, results revealed a water retention of 97% for TGBR, 100% for EGR8, and 94% for EGR16. For medium rain events, only 18% were retained by TGBR, 86% by EGR8, and 70% by EGR16. For heavy rain events, only 17% of the water was retained by TGBR, 82% by EGR8, and 68% by EGR16. Therefore, the water retention ability and the runoff dynamics of EGRs depend on the weather conditions and characteristics of EGRs. The weather conditions include intensity and duration of a rain event, drought time laps between two rain events, and atmospheric temperature and RH. The characteristics of EGRs include, thickness and type of the growing medium and roof slope. In particular, the presence of alumina in the substrate of EGR8 might be the reason behind the increase in water retention capability of EGR8. To compare, Carter and Rasmussen (2006) found that for small, medium, and large storms, 88%, 54%, and 48% rainfall were retained [41]. Simmons *et al.* (2008) stated that the retention of VRs was 100% for small rain events, between 88% and 26% for medium rain events, and between 44 and 13% for large rain events [42].

Table 5-4: Summary of the three types of rainfall events and their corresponding runoff water profiles for the studied roofs

Date	Light rain (mm)				Medium rain (mm)				Heavy rain (mm)			
	Rainfall	Runoff-TGBR	Runoff-EGR8	Runoff-EGR16	Rainfall	Runoff-TGBR	Runoff-EGR8	Runoff-EGR16	Rainfall	Runoff-TGBR	Runoff-EGR8	Runoff-EGR16
14 01 2016	0.25	0.00	0.00	0.00								
15 01 2016	0.51	0.00	0.00	0.00								
18 01 2016					7.87	24.64	0.51	1.78				
19 01 2016									33.02	27.43	53.59	103.12
19 01 2016					3.30	15.24	1.52	8.13				
20 01 2016					12.70	116.59	52.07	78.99				
20 01 2016	0.25	0.25	0.76	1.52								
21 01 2016	0.25	0.00	0.51	0.00								
23 01 2016					6.35	0.00	0.00	1.78				
25 01 2016									36.58	95.76	87.88	216.15
06 02 2016					27.43	201.42	2.79	8.89				
08 02 2016									30.48	231.39	42.93	10.16
11 02 2016	0.51	0.00	0.00	0.00								
22 02 2016					11.18	45.21	3.56	6.60				
03 03 2016	1.27	0.00	0.00	0.25								
14 03 2016	1.78	0.00	0.00	0.00								
15 03 2016									33.27	107.95	5.84	9.91
16 03 2016					28.70	166.88	3.56	8.38				
17 03 2016					3.05	4.83	0.25	0.76				
21 03 2016					2.03	0.00	0.00	0.51				
21 03 2016	1.02	0.00	0.00	0.25								
22 03 2016	1.02	0.25	0.00	0.00								
28 03 2016					20.57	93.98	1.78	5.59				
28 03 2016					3.81	20.32	0.76	0.76				
29 03 2016					2.03	0.00	0.00	0.51				

5.4.5 Influence of the slope on the water runoff

The roof slope, and intensity of rain events, and media depth and composition highly affect the water retention dynamics of VRs. Results revealed that for a light rain event (e.g. March 21, 2016), the dry EGR8 at 0% slope retained 100% of the rainfall compared to 75% for EGR16 at 6% slope. For a medium rain event (e.g. January 23, 2016), the wet EGR8 at 0% slope also retained 100% of the waterfall versus 72% for EGR16 at 6% slope. As for a heavy rain event (e.g. March 15, 2016), EGR8 at 0% slope held 82% of the waterfall versus 70% for EGR16 at 6% slope. Therefore, results revealed the influence of the slope on the water retention capacity of EGRs. VanWoert *et al.* (2005) [39] illustrated that for a 40 mm rain event, the water retention was recorded highest (87%) at 2% slope and lowest (65.9%) at 6.5% slope. More to the point, for a 2 % slope, the retention was 62% for a simulated rain event intensity of 0.4 mm/min and 21% for a simulated rain event intensity of 1.3mm/min as stated by Villarreal and Bengtsson (2005) [40]. For a 14 % slope and simulated rain event intensity of 0.4 and 1.3 mm/min, the water retention was 39% and 10%, respectively.

5.4.6 Runoff water quality

5.4.6.1 pH

The average pH of runoff water from EGR8 and EGR16 was significantly higher than that of rain water and runoff water from TGBR. Furthermore, the average pH of runoff water from EGR16 was lower than from EGR8 (**Figure 5-7.a**). The outcomes of this work confirmed the ones obtained by Teemusk and Mander (2007) [46], Czemieli Berndtsson *et al.* [47], and Bliss *et al.* (2009) [48] who found the pH of runoff water from VR between 7 and 8 and the pH of rainfall water between 5 and 6. This is a very important environmental benefit especially when the roof runoff is directly discharged to natural water recipients, this indicates that VRs can mitigate urban acid rain runoff and protect terrestrial ecosystems, historical buildings, and building materials. [49, 50].

5.4.6.2 Nutrients and heavy metals

The average load of nutrients (*Ca* and NH_4^+) and heavy metals (*Cd*, *Cu*, *Fe*, *Cr*, and *Zn*) in rainfall water and in runoff water from TGBR, EGR8, and EGR16 are indicated in **Figure 5-7**. The average load values of *Cd*, *Cu*, *Fe*, *Cr*, and *Zn* in rain water was higher than that in runoff water from TGBR, EGR8, and EGR16. Moreover, the average of *Cd*, *Cu*, *Fe* and *Ca*

loads in runoff water from EGR8 was lower than that in runoff water from EGR16. The average of Cr, Zn, and NH_4^+ loads in runoff water from EGR8 was higher than that in runoff water from EGR16. Also, the average of NH_4^+ load in runoff water from EGR8 was higher than that in rain water and in runoff water from TGBR and EGR16. Furthermore, the average of Ca load in runoff water from TGBR was higher than that in rain water and in runoff water from EGR8 and EGR16 (**Figure 5-7.b-h**).

Zhang *et al.* (2015) established that average Ca^{2+} and NH_4^+ concentrations in runoff water from VRs were significantly higher than that in runoff water from asphalt roofs and in rain water [19]. Also, Buffam *et al.* (2016) stated that NH_4^+ was the highest for rain water and the lowest for VRs assuming that VRs act as a sink for NH_4^+ [18]. In addition, Buffam *et al.* (2016) correlated the variation of Ca concentration to seasons where the highest values were recorded in summer, the lowest ones in winter, and the intermediate ones during fall and spring. However, little or no seasonal variations were recorded for pH and dissolved metals (Fe, Zn) [18]. Moreover, median Zn concentration in runoff water from VRs was at least tenfold higher than that in rain water during summer [18]. Accordingly, the findings in this research are in agreement with the outcomes of Berndtsson (2010) [3] where heavy metals loads in runoff water from hard surfaces were higher than that in runoff water from VRs (EGR with vegetation retained 44% Cu, 72% Zn, 62% Cd, and 91% Pb) [3]. Likewise, Alsup *et al.* (2013) [51] showed that VRs were generally acting as a sink for pollutants rather than a source of metals. In line with that, Gnecco *et al.* (2013) [52] concluded that VRs retained mainly zinc and copper while Ye *et al.* (2013) [53] stated that heavy metals were consumed by the roots of the vegetation. Consequently, upon the outputs of the chemical tests, heavy metals loads reduction is mainly dependent on the reduced runoff water volume and the maintenance level (usage of fertilizer).

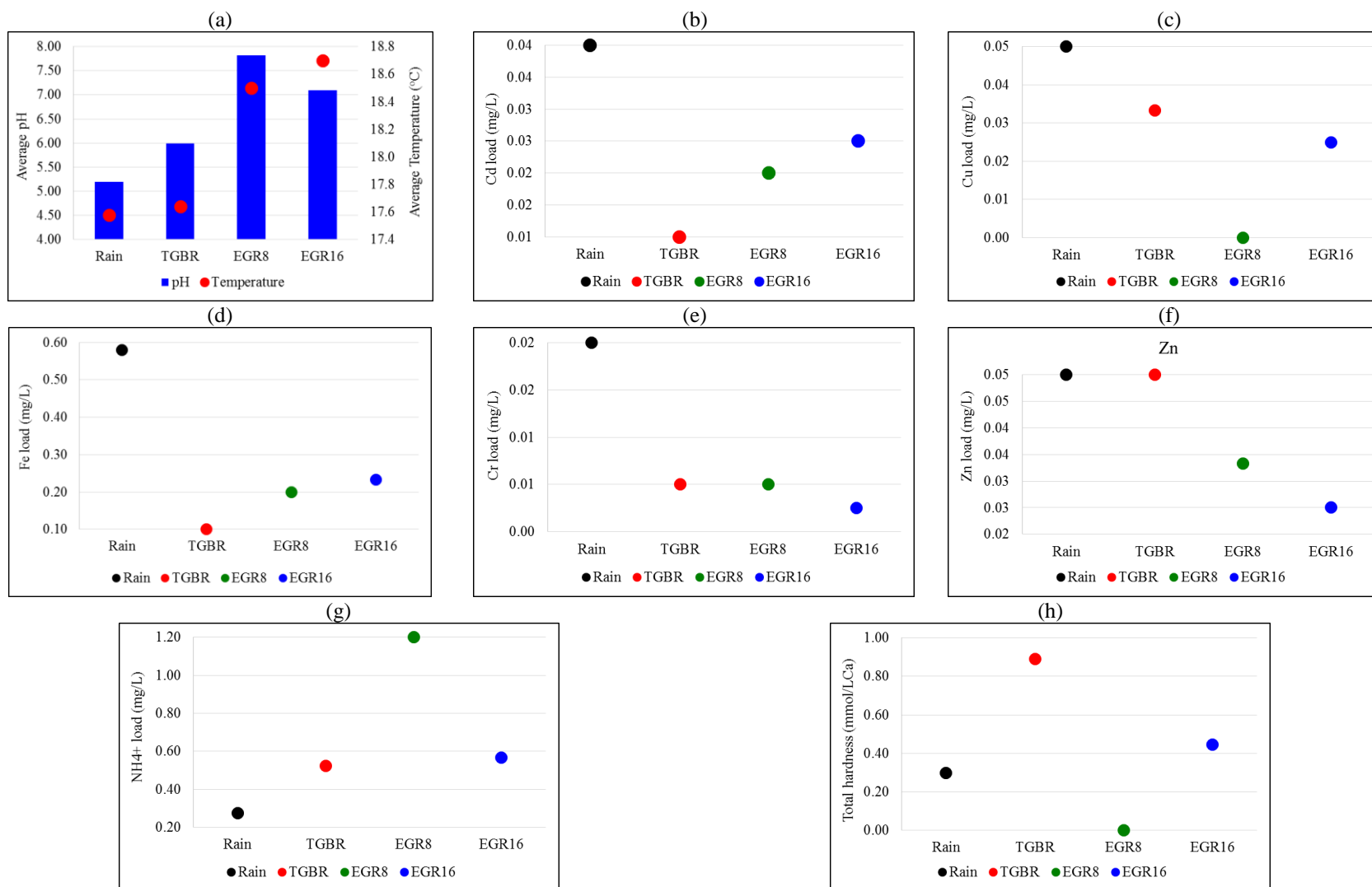


Figure 5-7: Average values of: (a) pH (b) Cd (c) Cu (d) Fe (e) Cr (f) Zn (g) NH_4^+ (h) total hardness

5.5 Conclusion and perspectives

The outcomes presented in this paper for a TGBR and two EGR mockups with different composition and substrate depth in the Mediterranean zone were studied for the first time in literature up to our knowledge. It was shown that an EGR effectively retained rainfall water if the rainfall events were not too intense (9 light (< 2mm) and 12 medium (< 30mm) rain events), the substrate layer was dry or not fully saturated, or if preceding days were rainless. Furthermore, the findings of this research confirmed the slope influence on the runoff water dynamics, as the water volume retained by the leveled EGR8 was higher than that retained by the sloped EGR16 (6% slope). As for the physical and chemical characteristics, *pH* values were greater for runoff water from EGR8 and EGR16 than that from TGBR and for rainwater. As a result, the Lebanese underground water, sea water, animals, and shells would be protected. Moreover, results revealed that EGRs generated better-quality runoff by reducing the amount of heavy metals and nutrients particularly when newly constructed compared to TGBRs. Both EGR configurations acted as a sink for various nutrients and heavy metals and improved runoff water quality, making wastewater treatment easier and cheaper. However, further studies highlighting the seasonal variability and new parameters such as pesticides and microbial pathogens in runoff water as well as VRs with different substrate ages are interesting in order to quantify and better understand the influence of VRs on stormwater runoff dynamics.

5.6 Acknowledgement

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5.7 References

- [1] Karteris, M., Theodoridou, I., Mallinis, G., Tsiros, E., & Karteris, A. (2016). Towards a green sustainable strategy for mediterranean cities: Assessing the benefits of large-scale green roofs implementation in thessaloniki, northern greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. *Renewable and Sustainable Energy Reviews*, 58, 510-525. doi:<http://dx.doi.org/10.1016/j.rser.2015.11.098>
- [2] Dunnett N, Kingsbury N. *Planting green roofs and living walls*. Portland, London: Timber Press Portland; 2004.

- [3] Czemieli Berndtsson, J. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, 36(4), 351-360. doi:<http://dx.doi.org/10.1016/j.ecoleng.2009.12.014>
- [4] Kosareo, L., Ries, R., 2007. Comparative environmental life cycle assessment of green roofs. *Build. Environ.* 42, 2606–2613.
- [5] Zhang, S., Guo, Y., 2013. Analytical probabilistic model for evaluating the hydrologic performance of green roofs. *J. Hydrol. Eng.* 18, 19–28.
- [6] USEPA, 2003. Cooling Summertime Temperatures: Strategies to Reduce Urban Heat Islands. USEPA, Washington, DC, EPA-430-F-03-014.
- [7] Li, J., Wai, O. W. H., Li, Y. S., Zhan, J., Ho, Y. A., Li, J., & Lam, E. (2010). Effect of green roof on ambient CO₂ concentration. *Building and Environment*, 45(12), 2644-2651. Doi: <http://dx.doi.org/10.1016/j.buildenv.2010.05.025>
- [8] Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and Environment*, 46(3), 729-738. Doi: <http://dx.doi.org/10.1016/j.buildenv.2010.10.006>.
- [9] Kim, KG. The application of the biosphere reserve concept to urban areas: the case of green rooftops for habitat network in Seoul. *Ann NY Acad Sci* 2004; 1023:187–214.
- [10] Van Renterghem, T., Booteldooren, D., 2009. Reducing the acoustical facade load from traffic with green roofs. *Build. Environ.* 44, 1081–1087.
- [11] Lin, Y., & Lin, H. (2011). Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. *Building and Environment*, 46(2), 345-355. Doi: <http://dx.doi.org/10.1016/j.buildenv.2010.07.027>.
- [12] Wilmers, F. (1990). Effects of vegetation on urban climate and buildings. *Energy and Buildings*, 15(3), 507-514. Doi: [http://dx.doi.org/10.1016/0378-7788\(90\)90028-H](http://dx.doi.org/10.1016/0378-7788(90)90028-H).
- [13] Meng, Q., Hu, W., 2005. Roof cooling effect with humid porous medium. *Energy Buildings* 37, 1–9.
- [14] Alexandri, E., & Jones, P. (2008). Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment*, 43(4), 480-493. Doi: <http://dx.doi.org/10.1016/j.buildenv.2006.10.055>

- [15] Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in athens, greece. *Energy*, 32(9), 1781-1788. Doi: <http://dx.doi.org/10.1016/j.energy.2006.11.011>.
- [16] Köhler, M., Schmidth, M., Grimme, F.W., Laar, M., de Assunc, ~ao Paiva, V.L., Tavares, S., 2002. Green-roofs in temperate climates and in the hot-humid tropics—far beyond the aesthetics. *Environ. Manage. Health* 13 (4), 382–391.
- [17] Brenneisen, S. The benefits of biodiversity from green roofs-key design consequences. 1st North American green roof conference: greening rooftops for sustainable communities. Chicago, IL: The Cardinal Group, Toronto; 2003. 323–329.
- [18] Buffam, I., Mitchell, M. E., & Durtsche, R. D. (2016). Environmental drivers of seasonal variation in green roof runoff water quality. *Ecological Engineering*, 91, 506-514. doi:<http://dx.doi.org/10.1016/j.ecoleng.2016.02.044>
- [19] Zhang, Q., Miao, L., Wang, X., Liu, D., Zhu, L., Zhou, B., ... Liu, J. (2015). The capacity of greening roof to reduce stormwater runoff and pollution. *Landscape and Urban Planning*, 144, 142-150. doi:<http://dx.doi.org/10.1016/j.landurbplan.2015.08.017>
- [20] T. Liptan, Integrating stormwater with site, street, and architectural design, in: *Proceedings of the 8th Biennial Watershed Management Council Conference on Managing Watersheds in the New Century*, American Society of Civil Engineers, Pacific Grove, CA, United States, (2000), p. 147.
- [21] Fioretti, R., Palla, A., Lanza, L. G., & Principi, P. (2010). Green roof energy and water related performance in the mediterranean climate. *Building and Environment*, 45(8), 1890-1904. doi:<http://dx.doi.org/10.1016/j.buildenv.2010.03.001>
- [22] Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, 77(3), 217-226. doi:<http://dx.doi.org/10.1016/j.landurbplan.2005.02.010>
- [23] Nawaz, R., McDonald, A., & Postoyko, S. (2015). Hydrological performance of a full-scale extensive green roof located in a temperate climate. *Ecological Engineering*, 82, 66-80. doi:<http://dx.doi.org/10.1016/j.ecoleng.2014.11.061>

- [24] Fardoun, F., Ibrahim, O., Younes, R., & Louahlia-Gualous, H. (2012). Electricity of lebanon: Problems and recommendations. *Energy Procedia*, 19, 310-320. doi:<http://dx.doi.org/10.1016/j.egypro.2012.05.211>
- [25] The World Bank. (2010). Republic of lebanon - water sector: Public expenditure review. (Public Expenditure Review No. 52024-LB).The World Bank.
- [26] Palla, A., Gnecco, I., Lanza, L., 2010. Hydrologic restoration in the urban environment using green roofs. *Water* 2, 140e154.
- [27] Razzaghmanesh, M., Beecham, S., Kazemi, F., 2014a. Impact of green roofs on stormwater quality in a South Australian urban environment. *Sci. Total Environ.* 470e471, 651e659.
- [28] Decagon Devices. (2015). EC-5 small soil moisture sensor. Retrieved from <https://www.decagon.com/en/soils/volumetric-water-content-sensors/ec-5-lowest-cost-vwc/>
- [29] CAMPBELL SCIENTIFIC. (2016). CR1000 measurement and control system. Retrieved from <https://www.campbellsci.com/cr1000>
- [30] CAMPBELL SCIENTIFIC. (2016). 16-channel or 32-channel relay multiplexer. Retrieved from <https://www.campbellsci.com/am16-32>
- [31] Tinytag. (2016). Rugged, waterproof temperature and relative humidity logger with built-in sensors. Retrieved from <http://www.geminidataloggers.com/data-loggers/tinytag-plus-2/tgp-4500>
- [32]<http://www.sigmaaldrich.com/catalog/search?term=AQUANAL%E2%84%A2-plus&interface=All&N=0&mode=match%20partialmax&lang=en®ion=LB&focus=product>
- [33] <http://www.wtw.com/en/products/product-categories/benchtop-meters/inolabr-benchtop-meters/inolabr-ph-7110.html>
- [34] Villarreal, E., 2007. Runoff detention effect of a sedum green roof. *Nordic Hydrol.* 38 (1), 99–105.
- [35] Köehler M. Urban storm water management by extensive green roofs. In *Proc. 38th world congress IFLA*, 24e26 Sept., Singapore; 2005. p. 124e33.

- [36] Scholz Barth, K., 2001. Green roofs: stormwater management from the top down. *Environ. Des. Constr.* 4 (1), 63–70.
- [37] Bengtsson, L., 2005. Peak flows from thin sedum-moss roof. *Nordic Hydrol.* 36 (3), 269–280.
- [38] Getter, K.L., Rowe, D.B., Andresen, J.A., 2007. Quantifying the effect of slope on extensive green roof stormwater retention. *Ecol. Eng.* 31, 225–231.
- [39] VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., Xiao, L., 2005. Green roofs stormwater retention: effects of roof surface, slope, and media depth. *J. Environ. Qual.* 34, 1036–1044.
- [40] Villarreal, E.L., Bengtsson, L., 2005. Response of a sedum green-roof to individual rain events. *Ecol. Eng.* 25, 1–7.
- [41] Carter, T.L., Rasmussen, T.C., 2006. Hydrologic behavior of vegetated roofs. *J. Am. Water Resour. Assoc.* 42 (5), 1261–1274
- [42] Simmons, M.T., Gardiner, B., Windhager, S., Tinsley, J., 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. *Urban Ecosyst.* 11, 339–348.
- [43] DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D. (2005). Stormwater mitigation and surface temperature reduction by green roofs. *Trans.ASAE* 48 (4), 1491–1496.
- [44] Moran, A., Hunt, B., Smith, J. (2005). Hydrological and water quality performance from greenroofs in Goldsboro and Raleigh, North Carolina. In: *Green Roofs for Healthy Cities Conference*, May 2005, Washington, DC.
- [45] Bengtsson, L. (2002). Avrinning fr°an gr°ona tak (Runoff from green roofs). *VATTEN* 58, 245–250.
- [46] Teemusk, A., Mander, Ü. (2007). Rainwater runoff quantity and quality performance from a green roof: the effects of short-term events. *Ecol. Eng.* 30, 271–277.
- [47] Czemieli Berndtsson, J., Bengtsson, L., Jinno, K., 2009. Runoff water quality from intensive and extensive vegetated roofs. *Ecol. Eng.* 30, 271–277.
- [48] Bliss, D.J., Neufeld, R.D., Ries, R.J., 2009. Storm water runoff mitigation using a green roof. *Environ. Eng. Sci.* 26 (2), 407–417.

- [49] Li, Y; Babcock Jr, RW. Green roofs against pollution and climate change. A review. *Agron Sustain Dev* 2014: 1–11.
- [50] Aitkenhead Peterson, JA; Dvorak, BD; Volder, A; Stanley, NC. (2011). Chemistry of growth medium and leachate from green roof systems in south-central Texas. *Urban Ecosyst* 14:17–33.
- [51] Alsup, S., Ebbs, S., Battaglia, L., & Retzlaff, W. (2013). Green roof systems as sources or sinks influencing heavy metal concentrations in runoff. *Journal of Environmental Engineering*, 139(4), 502-508.
- [52] Gnecco, I; Palla, A; Lanza, L; La Barbera, P. (2013). The role of green roofs as a source/sink of pollutants in stormwater outflows. *Water Resour Manag* 27: 4715–30.
- [53] Ye, J; Liu, C; Zhao, Z; Li, Y; Yu, S. (2013) Heavy metals in plants and substrate from simulated extensive green roofs. *Ecol Eng* 55:29–34.

CHAPTER 6 GENERAL DISCUSSION

VRs constitute technical, architectural, and environmental solutions that primarily allow an increase of roof base membrane lifetime, a reduction of buildings' energy demands, a delay and reduction of runoff water, an improvement of runoff water quality, as well as a mitigation towards air pollution. The conducted research assessed the impacts of VRs on the environment and runoff water quality, occupant hydrothermal comfort, in addition to thermal diffusion phenomenon and VWC at different growth medium depths during the winter season. In this respect, this work relied on a methodology that combines a numerical modeling with an experimental study of different roof types in order to answer the key research questions.

According to the literature review, heat diffusion and moisture through VRs is different from that through TGBR. Furthermore, the models proposed in the literature are often limited to heat and moisture transfer with only few studies pointing the extent to which VRs influence buildings. In particular, this study takes a great advantage in targeting Lebanon, a country in which no study to date has covered the impact of VRs on the environmental, energetic, and hydric performances of the buildings. Moreover, Lebanon lacks a clear sustainable plan and suffers from major problems in water and electricity sectors since the civil war (1975-1990) despite the existence of a major rehabilitation plan.

Toward this situation, a real EGR of 834 m² was numerically assessed from an environmental perspective through LCA methodology and compared to three fictitious roofs of the same area: TGBR, WRR, and IGR (1st manuscript). Both LCA and VRs are recent technologies in Lebanon where solely two EGRs are installed and only 57 LCA studies have been published (none of which is for the Lebanese VRs). Unlike earlier designs described in the literature, the developed LCA modelling is original in terms of the type of compared roofs and by being the first model of its kind to be examined for the Lebanese context. This unique model was then subject to experimental studies in order to better explore its energetic and hydric performances. In this respect, three roof mockups (one TGBR mockup and two EGR mockups different in the roof slope, in the composition and the thickness of their growing medium) were installed on the rooftop of the Chemical Engineering Department at the University of Balamand, in the region of El Koura, North Lebanon. The thermal diffusion process (2nd manuscript) and the moisture diffusion process (3rd manuscript) of TGBR and EGR mockups were evaluated during the winter season (in particular from the 14th of January 2016 to the 31th of March 2016).

This experimental work was, to date, very innovative in its scientific content. This is because, no study had yet elaborated the energetic and hydric perspectives of VRs for the Lebanese context. Also, EGRs with the proposed substrate depths and composition have never been treated in literature. More to the point, the literature lacks research about thermal and hydric diffusion processes through the substrate and about seasonal VRs' influence on runoff dynamics (quantity and quality) in the Middle East zone.

From an environmental perspective, EGRs had the lowest potential environmental impact for most of the 15 studied impact categories compared to TGBR, WRR, and IGR. A further look to the contribution of each roof components to the potential environmental impacts, the ready mixed concrete, rebar, and waterproof membrane were the main contributors. In addition, sensitivity and uncertainty analyses were performed to check the robustness of the results. These analyses showed that the variation of the rebar amount affect the roof potential environmental impacts for most of the impact categories unlike the case of the variation of the fertilizer and concrete amounts.

In parallel, experimental study was performed for a TGBR and two EGRs that differ in the roof slope and in the composition and the depth of the growing medium. In particular, the leveled EGR8 with 8 cm media depth was composed of soil, peat, alumina, pumice, and fertilizer whereas the sloped EGR16 (6% slope) with a 16 cm media depth was made of soil, peat, pumice, and fertilizer. The experimental study was done to assess the following: temperature profile at different substrate depths, heating and cooling demands of a residential building, moisture content at different substrate depths, and runoff water quality. The soil temperature and moisture at different depth were recorded using thermocouples and soil moisture sensors every minute for the entire measurement period. The temperature fluctuations of the base roof membrane were highly reduced due to the presence of the substrate layer. Unexpectedly, the variation of daily temperature amplitude for EGR8 and EGR16 surfaces was higher than that for TGBR surface; this is mostly due to the weak “mask effect” of the plants. The variation of daily temperature amplitudes at the depth of 4, 6 and 8 cm of EGR8 were similar. Likewise, the variation of daily temperature amplitudes at the depth of 6, 11 and 16 cm of EGR16 were very close. In addition, for both EGR8 and EGR16, the maximum thermal insulation properties were reached at the depth of 6 cm regardless the substrate composition and depth. Also, in a typical cold winter day, the temperature values under the substrate layer were warmer than that of air. This difference was not as noticeable as for a sunny winter day ($T_{air\ max} = 32^{\circ}C$) where air temperatures were highly reduced due to the substrate layer indicating the passive cooling

effect. In parallel, the temperature profile at different substrate depths was used to determine the heating/cooling demand of a residential house which, in turn, were converted to heating/cooling cost. Those costs together with the construction cost of 1 m² of TGBR and EGR were utilized to establish a full economic study. Results revealed that EGR could lead to savings of up to 45USD/200m²/month compared to TGBR.

The second part of the experimental study was dedicated to the evaluation of the water management performance and runoff dynamics of TGBR and EGR mockups. First, air RH at 5 and 110 cm heights were mainly identical but much higher than the WC of the substrate layer at the depth of 8 and 16 cm of EGR8 and EGR16, respectively. Second, the vertical variability of soil moisture was recorded every minute. Results depicted that, for EGR8, the WC at the depth of 8 cm was noticeably lower than that at the depth of 4 and 6 cm. Therefore the rainfall water was predominantly absorbed by the first 6 cm before reaching the bottom of the substrate (depth of 8 cm). As for EGR16, the WC at the depth of 16 cm was very close to that at the depth of 6 and 11 cm. This clearly explains the discrepancy between both water retention profiles. Additionally, each roof mockup was mounted with a rain water gauge in order to investigate the delay and the runoff water volume. During the entire measurement period, the total of 25 rainfalls was distributed as 9 light (< 2 mm), 12 medium (< 30 mm), and 4 heavy (> 30 mm) rain events. For light rain events, the water retention was 97% for TGBR, 100% for EGR8, and 94% for EGR16. For medium rain events, only 18% was retained by TGBR, 86% by EGR8, and 70% by EGR16. For heavy rain events, only 17% was retained by TGBR, 82% by EGR8, and 68% by EGR16. Therefore, the water retention capacity of VRs was dependent on the rain event size and intensity, the drought time lag between two rain events, in addition to the substrate depth and composition. Hence, the quality of rainfall water and that of runoff water from TGBR, EGR8, and EGR16 were performed using chemical tests. In total, seven color comparator tests were carried out to quantify the pH values, Cd, NH₄⁺, Cu, Cr, Fe, Ca, and Zn loads. Average pH of rain water and that of water runoff from TGBR were significantly lower than that from EGR8 and EGR16. Results show that runoff water from EGRs, particularly when newly constructed, contained high level of nutrients and heavy metals (especially Cd, Fe, Ca²⁺, and NH₄⁺). Consequently, both EGR configurations acted as a sink for various nutrients and metals, and generated better-quality of runoff water compared to TGBR.

Based on the numerous findings of this research, VRs seem to be an effective remedy of many problems in Lebanon. First, the reduced need for heating and cooling systems leads to a

decrease in the electricity consumption which in return, will reduce the electricity deficit. Second, delaying and reducing the runoff water from EGRs compared to TGBRs will efficiently lower the flooding of urban roads and will save the country thousands of dollars, if not more. Furthermore, the improvement of the runoff water quality saves natural as well as sea water, and helps in building a clear and strong sustainable plan. Besides, VRs, similarly to any new sustainable technologies in Lebanon (e.g. solar panels), would create several job opportunities including suppliers of different roof's layers, roof consultants, engineers, and companies supplying maintenance contracts. Finally, the joint added value of VRs should lead the journey for Lebanese decision makers in the environmental ministry, order of engineers, NGOs, and others to push laws or policies for commercial constructions (shops, restaurants, malls...) to be totally or partially covered by VRs through tax deductible policies. More to the point, architects should be encouraged to introduce VRs in new residential buildings through special bank loans for green buildings. This will not only bring dramatic changes to skylines and bolster the efficiency of commercial zones, but will also speed up the pace of solar adoption in Lebanon.

CONCLUSION

This research focused on the evaluation of environmental and energy performances of VRs and the assessment of their rainwater management potential. This thesis has allowed the development of new theoretical and experimental studies for the Lebanese country but that could be extrapolated for use in other geographical contexts. Results could be used by civil and environmental engineers for the installation of new roofs, the modification of existing ones, and/or for policy making to encourage the implementation of green surfaces in Lebanon. A summary of these contributions as well as recommendations and perspectives for future research are presented in this chapter.

6.1 CONTRIBUTION

This work allowed assessing:

- The potential environmental impacts of a real EGR installed at the Central Bank of Lebanon in comparison with three fictitious roofs: TGBR, WRR, and IGR. The determination of the potential environmental impacts of the roofs was accomplished through the use of LCA modelling. VRs are still a new technology in Lebanon. This is the first LCA study on VRs in this country. The roofs were all assumed to be 834m² (same as the area of the existing EGR) and their lifetime was assumed to be 45 years. The LCA modeling showed that, to decrease the environmental impacts of the studied roofs, the focus should be on decreasing the usage of mastic asphalt for TGBR, white reflective membrane for WRR, and thermal insulation and perlite for VRs more than on the core construction materials (rebar and concrete) that are mainly unmodifiable and unreplaceable. For instance, mastic asphalt could be replaced by SBS membrane or perlite might be substituted by other type of aggregate that have low environmental impacts (1st manuscript).
- The thermal profile of EGRs mockups in comparison with TGBR mockup through real-time temperature monitoring. In particular, one TGBR and two EGRs mockups equipped with thermocouples between their different layers and at different substrate

depths were installed on the rooftop of the Chemical Engineering Department at the University of Balamand in north Lebanon. The temperature profile in winter season was used to determine the heating/cooling demands of a residential house which, in turn, were converted to heating/cooling costs. Those costs together with the construction cost of 1m² of TGBR and EGR were utilized to establish a full economic study of a residential Lebanese building with an average surface of 200m². These types of mockups as well as the temperature profile of this substrate composition and depth had not been explored to date neither at the national level nor at the international level (2nd manuscript).

- The stormwater management and runoff dynamics of two EGRs mockups compared to TGBR mockup. EGRs mockups were distinguished by their roof slope and their growth medium material and depth (EGR8 has 0% slope, with 8 cm media depth, and without alumina while EGR16 has 6% slope, with 16 cm media depth, and with alumina). The stormwater management was assessed through a real-time soil moisture (volumetric water content) monitoring at different substrate depths during the Lebanese winter season. Also, the quality of the rainfall water as well as the quality of runoff water from TGBR, EGR8, EGR16, were quantified by determining the pH values, nutrients, and heavy metals loads. The experimental study demonstrated that VRs are very interesting for Lebanon, a country that still suffering from road flooding and water shortages (3rd manuscript).

The following findings were obtained:

- EGRs are the best roofs as they had the least potential environmental impacts compared to TGBR, WRR, and IGR,
- The reinforcing metal bars and ready concrete are the main contributors to the potential environmental impacts of TGBRs. The reinforcing metal bars, ready concrete, and waterproof membrane are the main contributors for EGRs, while the reinforcing metal bars, ready concrete, waterproof membrane, and growing medium are the main contributors for IGRs,
- VRs are more aesthetically pleasant than TGBR and WRR,
- EGRs highly reduce the temperature fluctuations of the base roof membrane compared to TGBR,

- An EGR with a substrate layer of 6 cm of both compositions is sufficient to reach the highest thermal insulation properties,
- The passive cooling effect of EGRs was noticeable even in a sunny winter day ($T_{\text{air max}} = 32^{\circ}\text{C}$) thus the energy consumption is reduced,
- The joint added values of EGRs could lead to money saving up to 45US\$/200m²/month compared to TGBR,
- EGRs totally retain light rain events compared to TGBR,
- EGRs efficiently retain moderate rain events compared to TGBR even if the growth medium was wet from previous rainfall,
- EGRs slightly retain heavy rain events compared to TGBR and the water runoff was not relatively delayed,
- Runoff water from EGR8 was reduced and delayed compared to TGBR and EGR16 mostly because of the presence of alumina in the substrate composition of EGR8,
- The water volume retained by the leveled EGR8 was higher than that retained by the sloped EGR16 (6% slope) therefore, the roof slope directly affect the water runoff dynamics even if preceding days were rainless,
- pH values of runoff water from EGRs mockups were higher than that of rainfalls water, therefore lowering the water acidity degree,
- EGRs acted as a sink for Cd, Fe, Ca, and NH₄⁺ compared to TGBR, particularly when newly constructed, thus EGRs generated a better runoff water quality.

6.2 RECOMMENDATIONS AND FUTURE DIRECTIONS

This thesis has allowed to broaden the knowledge predominantly on the evaluation of environmental, energetic, and hydric aspects of VRs. In addition, it helped to identify the following recommendations and perspectives for future research:

- A full cradle-to-grave LCA of VRs in the Lebanese context should be performed. In particular, a cradle-to-gate LCA was performed in this study. Addition of use and end-of-life phases could lead to different outcomes.

- The VRs effect on air quality, wildlife habitat, and biodiversity can be explored. Air quality could be assessed through real-time monitoring and quantification of airborne pollutants.
- The slope on the water runoff dynamics from VRs could also be explored. This can be done through the installation of VRs mockups with different slopes.
- Investigate new parameters such as pesticides and microbial pathogens in the runoff water from VRs compared it to that of rainwater and to the runoff water from TGBR using purity pesticide, pesticide metabolite standards, and reference materials.
- The stormwater management and runoff dynamics of IGRs in the Mediterranean climate can also be explored. This can be done by installing IGR mockup and evaluating its water management performance.
- The seasonal variability of both the temperature profile and the water retention of VRs should be studied to better understand the seasonal influence on energy savings, stormwater runoff, and water runoff quality.

APPENDIX

APPENDIX A: Life Cycle Assessment Phases

Starting 1990, the Society of Environmental Toxicology and Chemistry (SETAC) organizes various conferences and series of important workshops leading to the development of LCA. The results of all these meetings were assembled in the famous SETAC-triangle presented in **Figure 1**.

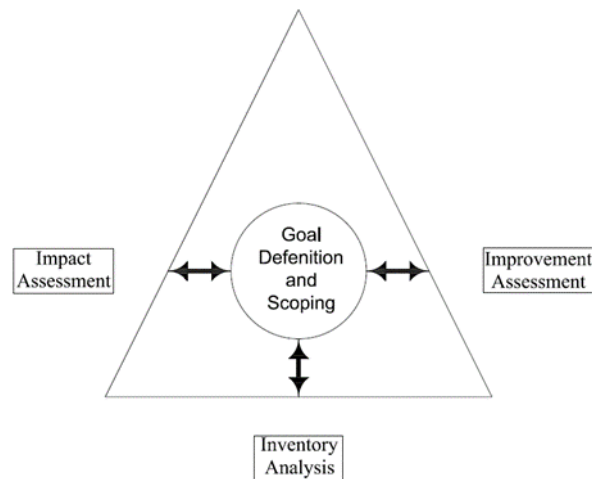


Figure 1: SETAC triangle

The main difference between SETAC-triangle and the actual structure defined by the International Standardization Organization is in the nomination of the “Improvement assessment” element. It is called "Interpretation" in the international standard ISO 14040 in 2006. Agreeing with ISO standards, LCA has four phases to consider: goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation.

1 Goal of the study

It is normal that each study has a goal, in particular a LCA study. The ISO standards have some specific necessities in order to define the goal:

- Describe the application and define the audience that will check the results of the study.
- Outline if the results will be internally communicated or will aim for a public comparison between two products.
- State the reasons for carrying out the study: providing information or improving a product.

2 Function of the study

The function of a study is directly related to the main purpose of the studied system. The quantification of this function is established on the implementation and application of the system over a specified period of time.

3 Functional unit of the study

The functional unit realizes the equivalence between different systems and it is an indispensable comparison element. Delimiting the functional unit is not always easy and obvious. For example, an orange juice carton is used for one time while the returnable bottle is used at least ten times. If the LCA aims on comparing the packaging systems of the orange juice, it is impossible to compare one orange juice carton to one bottle. The right approach is to compare two methods of packaging and supplying 1000 liters of orange juice. In this case, 1000 orange juice cartons are compared to 100 bottles and 900 washings assuming that each bottle is washed 9 times.

4 Reference flow of the study

The reference flow is equal to the quantity of products needed to perform the function of the study. From the previous example, we can deduce that the reference flow is 1000 orange juice cartons and 100 bottles.

5 Boundaries of the study

The concept of the system boundaries is a group of criteria defining the scope of the analysis, specifying the unit processes or activities as well as outlining the Life Cycle Stages (LCS) included in the study. Thus, it is not necessary that all the inputs and outputs in a product's Life Cycle are taken into consideration knowing that the omission of certain parts might affect the results. For example, the LCA stages of a roofing system are: extraction of raw materials, roof production, roof installation, use, maintenance, and end-of-life.

6 Life Cycle Inventory analysis

6.1 Data calculation

The data collection step is followed by the data calculation step. This step is essential in order to produce the inventory results for each unit process as well as for the functional unit of the defined system. Data calculation includes:

- Data validation
- Connecting the collected data to unit processes
- Linking the collected data to the reference flow of the functional unit

For example, the calculation of energy flow includes the sources of fuels and electricity, the effectiveness of the conversion and distribution processes, and the inputs and the outputs due to the generation and the use of the energy flow.

6.2 Allocation

Little industrial processes produce a single output but the majority of the industrial processes generates more than one product, and recycles the transitional or the discarded products as raw materials. When the systems involve several products and recycling systems, special care should be attributed to the allocation procedures.

6.3 Unit processes and system processes

In SimaPro database, each process or material is available in two versions: unit processes and system processes. Although the final outcomes are not highly affected by these two versions, some considerations should be taken into account when selecting between them.

- A unit process version contains only emissions and resource inputs from one process step, plus references to input from other unit processes. The unit process is a part in the product's life and is included within primary resource acquisition, raw material processing, and manufacturing. Its identification facilitates the quantification of the inputs and outputs, or "flows," at each phase of the life cycle.
- The system process values the consumption of resources and the emission of each process (raw materials extraction, production, use and disposal) in the product life cycle. **Table 1** summarizes the difference between unit processes and system processes.

Table 1: Unit processes and system processes differences

Unit processes	System processes
Complex process tree allowing the assessment of the contribution of all individual unit processes	Simple process tree
Holds uncertainty information (Monte Carlo)	No uncertainty information
Slow calculation	Fast calculation

7 Life Cycle Impact Assessment

7.1 Principles of Life Cycle Impact Assessment

7.2 Classical impact assessment methodologies

The classical impact assessment methodologies categorize and characterize LCI results in midpoint categories by quantifying midpoint CFs. These methods are split into the Centre of Environmental Science - Leiden University (CML) and the Environmental Design Of Industrial Products (EDIP).

7.2.1 Centre of Environmental Science - Leiden University (CML)

In 2001, some impact categories and characterization methodologies were suggested by scientists under the lead of Center of Environmental Science-Leiden University (CML). The resulting impact assessment methodology was defined as a midpoint approach and implemented as CML-IA. It includes Normalization but excludes weighting and addition.

In SimaPro 8, this method is available in two versions. The first method is the “baseline” version and the second one is the “extended” version. The first methodology includes 10 impact categories while the second methodology comprises all impact categories. Other impact categories as well as variations of existing impact categories are also part of the “extended” version.

7.2.2 Environmental Design of Industrial Products (EDIP)

7.2.2.1 EDIP97

The Life Cycle Impact Assessment EDIP97 method is a midpoint approach including most of the environmental impacts and resource use. Normalization is based on person equivalents whereas the weighting is based on the political reduction targets and the supply horizon for the environmental impacts and the resource use respectively. The key-property is a simple approach used to model the Ecotoxicity and human toxicity impact categories. In fact, in this approach, most of the important characteristics are enclosed in a simple modular framework that requires data of many substances for the calculation of the CFs.

7.2.2.2 EDIP 2003

The EDIP2003 method is a Danish endpoint approach or damage oriented approach that is an update of the EDIP 97 methodology. The characterization models cover a part of the environmental mechanism larger than the part covered by the EDIP97 methodology. The revolution in this method is the inclusion of the non-global impact categories (photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity, noise) in the life cycle impact assessment. In addition to that, the CFs for site-generic effects are only implemented in SimaPro 8.

7.2.3 Damage oriented assessment methodologies

7.2.3.1 ReCiPe

The heir of Eco-indicator 99 and CML-IA methods is the ReCiPe methodology for the LCIA. The latter was created by the National Institute for Public Health and the Environment in the Netherlands (RIVM), the Institute of Environmental Sciences (CML), PRé Consultants, and Radboud University. This assessment methods aims on transforming the extended list of LCI results into a restricted number of indicators. ReCiPe method integrates and matches the midpoint approach (CML-IA method) and the endpoint approach (Eco-indicator 99 method) in a reliable framework. The midpoint characterization factors are multiplied by damage factors, to obtain the endpoint characterization values.

7.2.3.2 Eco-indicator 99

The Eco-indicator 99 is the updated version of the Eco-indicator 95, is a damage-oriented approach, measures various environmental impacts, and shows the final results as a single score. The weighting step, the most complicated step in an LCIA, was the starting point for the development of the Eco-indicator methodology. Thus, the most important impact categories are grouped into human health, ecosystem quality, and Resources damages categories (endpoints).

▪ Human Health

The Human Health damages are expressed in Disability Adjusted Life Years (DALY). This damage category includes climate change, ozone layer depletion, ionizing radiation, respiratory effects, and carcinogens impact categories.

▪ Ecosystem Quality

The Ecosystem Quality damages are evaluated as the percentage of affected (PAF) or disappeared (PDF) species in a certain area/region due to the environmental load. As it is not an apparent damage, a conversion factor is used to translate the toxic stress into a real observable damage. This damage category comprises the regional effect on vascular plant species, the local effect on vascular plant species, the acidification and eutrophication, and the ecotoxicity impact categories.

▪ Mineral and fossil resources

The damage to mineral and fossil Resource is related to a parameter indicating the quality of the remaining mineral and fossil resources. This damage category contains the surplus energy for future extraction impact category.

The principal and important restrictive supposition is that in general all emissions and land uses are happening in Europe therefore all related damages happen in Europe. However, this assumption does not include the resources damages and the damages due to climate change, ozone layer depletion, carcinogenic substances, inorganic pollutants, and some radioactive substances. Figure 1 34 shows a detailed representation of the Eco-indicator 99 categories.

7.2.3.3 EPS2000

The default impact assessment method in the Environmental Priority Strategies (EPS) system is the damage oriented EPS 2000d impact assessment method. This methodology assists the designers and the developers in selecting between two product concepts and defining which one of two product concepts has the lowest environmental impacts. The EPS 2000 default method is an update of the 1996 version. The category indicators are: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values.

The LCIA methodologies detailed above are all limited. They are midpoint or endpoint oriented or they do not include all impact categories. UNEP-SETAC exploits the advantages of both approaches by grouping similar category endpoints into a structured set of damage categories in order to get the famous IMPACT 2002+ LCIA methodology.

8 IMPACT 2002+

The following sections shortly describe the main assessment characteristics for midpoint and damage categories, as well as related normalization factors.

8.1 Impact categories

8.1.1 Midpoint categories

The scope and the main challenges of each of the 14 midpoint categories are detailed in this section. **Tables 2, 3, and 4** represent, respectively, the midpoint categories and their indicators, the midpoint categories and their characterization factors as well as the endpoint categories, their indicators and their characterization factors.

8.1.1.1 Human toxicity

As its name implies, human toxicity impact category evaluates the impacts of toxic substances on human health. The characterization factors are given for air emissions only and the midpoint reference substance is chloroethylene (C_2H_3Cl) into air. The damage and the midpoint CFs are expressed in DALY/kg (obtained from IMPACT 2002 model) and in kg C_2H_3Cl into air-eq/kg respectively.

Human toxicity is mainly characterized by:

- General factors are considered at a continental level for Western Europe
- CFs are available for air, water, soil and agricultural soils [“soil (agr.)”] emissions.
- CFs are not available for emissions into ocean, underground water and stratospheric.

In 2010, Sanscartier et al introduce a new characterization factor for C_{10} - C_{50} hydrocarbons (excluding benzene and PAH) into water emissions. The midpoint and the damage CFs are equal to 0.0015 C_2H_3Cl into air-eq/kg and 4.21×10^{-9} DALY/kg respectively.

8.1.1.2 Respiratory (inorganics)

The respiratory impact category is caused by the inorganic substances. The characterization factors are given for air emissions only and the midpoint reference substance is particulate matter ($PM_{2.5}$) into air. The damage and the midpoint CFs are expressed in DALY/kg (obtained from Eco-indicator 99) and in kg $PM_{2.5}$ into air-eq/kg respectively. Agreeing with Dockery and Pope, carcinogenic effects are due to PM particles less than $2.5\mu m$ since particles above $2.5\mu m$ cannot enter the lung.

8.1.1.3 Photochemical oxidation (organics)

The photochemical oxidation impact category is due to the organics substances. The characterization factors are given for air emissions only and the midpoint reference substance is ethylene (C_2H_4) into air. The damage and the midpoint CFs are expressed in DALY/kg (obtained from Eco-indicator 99) and in kg C_2H_4 into air-_{eq}/kg respectively.

8.1.1.4 Ionizing radiation

The ionizing radiation impact category is caused by the radioactive material released to the environment. The characterization factors are given for air and water emissions only. The midpoint reference substance is carbon-14 (C_{14}) into air. The damage and the midpoint CFs are expressed in DALY/Bq (obtained from Eco-indicator 99) and in Bq C_{14} into air-_{eq}/Bq respectively.

8.1.1.5 Ozone layer depletion

The imperative reason of the ozone layer depletion impact category is the high level of chlorine and bromine. The characterization factors are given for air emissions only and the midpoint reference substance is trichlorofluoromethane (CFC-11) into air. The damage and the midpoint CFs are expressed in DALY/kg (obtained from Eco-indicator 99) and in kg CFC-11 into air-_{eq}/kg (obtained from the U.S. EPA ozone depletion potential list) respectively.

8.1.1.6 Aquatic acidification

The aquatic acidification impact category is due to the emission of nitrogen and sulfur oxides during fuel oil and coal combustion. The characterization factors are given for air, water and soil emissions. The midpoint reference substance is sulfur dioxide (SO_2) into air. The damage and the midpoint CFs are expressed in $PDF \cdot m^2 \cdot y/kg$ and in kg SO_2 into air-_{eq}/kg (obtained from CML) respectively.

8.1.1.7 Aquatic ecotoxicity

The aquatic ecotoxicity impact category is caused by heavy metals emitted in ions form. The characterization factors are given for air, fresh water (streams and lakes) and soil emissions. The midpoint reference substance is Triethylene glycol (TEG) into water. The damage and the midpoint CFs are expressed in $PDF \cdot m^2 \cdot y/kg$ (obtained from IMPACT 2002 model) and in kg TEG into water-_{eq}/kg respectively.

In 2010, Sanscartier et al introduce a new characterization factor for C₁₀ -C₅₀ hydrocarbons (excluding benzene and PAH) into water emissions. The midpoint and the damage CFs are equal to 0.013kg TEG into water-_{eq}/kg and 6.53×10^{-7} PDF·m²·y/Kg respectively.

8.1.1.8 Aquatic eutrophication

The aquatic eutrophication impact category is due to inorganic substances (sulphate, nitrate and phosphate) deposition. The characterization factors are given for air, water and soil emissions. The midpoint reference substance is phosphate (PO₄³⁻) into water. The damage and the midpoint CFs are expressed in PDF·m²·y/kg and in kg PO₄³⁻ into water-_{eq}/kg (obtained from CML) respectively. CFs are available in three different versions: P-limit, N-limit and undefined; P-limit version is applied as the default version within IMPACT 2002+.

8.1.1.9 Terrestrial acidification & nitrification

The terrestrial acidification & nitrification impact category is caused by the atmospheric emission of nitrogen (N) and sulfur (S). The characterization factors are given for air emissions only and the midpoint reference substance is sulfur dioxide (SO₂) into air. The damage and the midpoint CFs are expressed in PDF·m²·y/kg (obtained from Eco-indicator 99) and in kg SO₂ into air-_{eq}/kg respectively.

8.1.1.10 Terrestrial ecotoxicity

The terrestrial ecotoxicity impact category is due to heavy metals emitted in ions form. The characterization factors are given for air, water and soil emissions. The midpoint reference substance is Triethylene glycol (TEG) into soil. The damage and the midpoint CFs are expressed in PDF·m²·y/kg (obtained from IMPACT 2002 model) and in kg TEG into soil-_{eq}/kg respectively.

In 2010, Sanscartier et al introduce a new characterization factor for C₁₀ -C₅₀ hydrocarbons (excluding benzene and PAH) into water emissions. The midpoint and the damage CFs are equal to 0.11 kg TEG into soil-_{eq}/kg and 8.70×10^{-4} PDF·m²·y/Kg respectively.

8.1.1.11 Land use

The land use impact category is due to the concentration of toxic chemicals, to the nutrient and acid levels, to the increased UV patterns, and to the climate changes. That's why it is very difficult to separate the of land use effects from other impact categories. The characterization factors are given for occupation effects as well as soil emissions such as pesticides and

fertilizers. The midpoint reference flow is organic arable land·y. The damage and the midpoint CFs are expressed in $\text{PDF} \cdot \text{m}^2 \cdot \text{y} / \text{kg}$ (obtained from Eco-indicator 99) and in $\text{m}^2 \text{Org arable land}_{\text{eq}} \cdot \text{y} / \text{m}^2 \cdot \text{y}$ respectively. In fact, in Eco-indicator 99, land use is split into land occupation and land conversion while in IMPACT 2002+ only land occupation is deliberated.

Mostly in all Europe, land use effects are more momentous than the effects of many other impact categories because the modifications in land cover do not only affect a specific local area but the nearby regions as well.

8.1.1.12 Global Warming

The global warming impact category is caused by carbon dioxide, methane, and nitrous oxide emissions. The characterization factors are given for air emissions only. The midpoint reference substance is carbon dioxide (CO_2) into air. The damage and the midpoint CFs are expressed in $\text{kg CO}_2 \text{ into air}_{\text{eq}} / \text{kg}$, and they are obtained from IPCC list.

8.1.1.13 Mineral extraction

The mineral extraction impact category is due to the energy needed for the extraction processes. The midpoint reference substance is iron into ore. The damage and the midpoint CFs are expressed are expressed in MJ per extracted unit and obtained from Eco-indicator 99. The midpoint CFs could be weighted in $\text{kg iron in ore}_{\text{eq}} / \text{kg}$ extracted but this is not endorsed for use.

8.1.1.14 Non-renewable energy

The non-renewable energy impact category is caused by the total primary energy extracted. The midpoint reference substance is crude oil which is equal to $860 \text{kg} / \text{m}^3$. The damage and the midpoint CFs are expressed in MJ per extracted unit and obtained from Ecoinvent. The midpoint CFs could be weighted in $\text{kg crude oil}_{\text{eq}} / \text{kg}$ extracted but this is not endorsed for use.

8.1.2 Damage categories

8.1.2.1 Human health

The Human Health (HH) of any individual in the present or the upcoming generation could be damaged by the reduction of its lifetime (premature dead) or by the affection of the functions of the body (disability). Damages in human health could be caused by environmental sources such as infectious diseases, cancer and eye damages due to the depletion of the ozone layer,

cardiovascular diseases, respiratory diseases due to the presence of volatile and soluble toxic chemicals in air, drinking water and food, and cancer resulting from the rays' ionization. In fact, these damages are not the complete list of damages to human health, damages from emissions of Cd and Pb, endocrine disrupters, allergic reactions, noise and odor are not modelled yet.

Human health damages are gathered and expressed in DALY (Disability Adjusted Life Years). DALY is the amount of toxic substances in tons per year and deliberates the body disabilities. This disability ranges between 0 and 1 where 0 means perfectly healthy and 1 means death.

8.1.2.2 Ecosystems

Ecosystems are heterogeneous and very complex thus it is very difficult to monitor and determine all damages inflicted upon them. For example, council of Europe lists the important attributes to mankind: biodiversity, aesthetic and cultural values, ecological functions and services, etc. It is clear we cannot model all these attributes on all levels and dimensions therefore the diversity of species is an adequate representative for the quality of ecosystems. Ecosystem damages are represented as Potentially Affected Fraction (PAF) or Potentially Disappeared Fraction (PDF) of species in a given area during a certain time. The unit for the damages to ecosystem quality is the PDF multiplied by the meter square and year.

8.1.2.3 Climate change

The damage category Climate Change (CC) is same as the “global warming” midpoint category. This damage category is evaluated by the discharge of some greenhouses gases like carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) to the atmosphere. Following the Intergovernmental Panel on Climate Change (IPCC) protocol, these emissions were converted to CO₂-equivalents. Therefore, the damage category CC is expressed in “kg CO₂-eq”.

8.1.2.4 Resources

The damage to resources is the sum of the “mineral extraction” and “non-renewable energy” midpoint categories and expressed in “MJ”. The indicator of the damage to resources is measured in US dollars in order of quantifying the financial loss of minerals and non-renewable energy resulting from an activity.

Table 2: Midpoint categories and indicators

Damage category	Midpoint category			Indicator name
	Name	Abb.	Reference substance	
Human Health	Human Toxicity (Carcinogens + Non-carcinogens)	HT	kg C ₂ H ₃ Cl into air-eq/kg	Hazard-weighted dose
	Respiratory Effects (inorganics)		kg PM _{2.5} into air-eq/kg	
	Photochemical oxidation (organics)	POF	kg C ₂ H ₄ into air-eq/kg	
	Ionizing Radiation	IR	Bq C ₁₄ into air-eq/kg	Absorbed dose
	Ozone layer Depletion	OD	kg CFC-11 into air-eq/kg	Stratospheric ozone concentration
Ecosystem diversity	Aquatic Acidification		kg SO ₂ into air-eq/kg	
	Aquatic Ecotoxicity	MET	kg TEG into water-eq/kg	Hazard-weighted concentration
	Aquatic Eutrophication	ME	kg PO ₄ ³⁻ into water-eq/kg	Nitrogen concentration
	Terrestrial acidification/nutrification	TA	kg SO ₂ into air-eq/kg	Base saturation
	Terrestrial Ecotoxicity	TET	kg TEG into soil -eq/kg	Hazard-weighted concentration
Climate change Resources Availability	Land Occupation	LO	m ² org arable into land-eq· y/m ² ·y	Occupation
	Global Warming	CC	kg CO ₂ into air-eq/kg	Infra-red radiative forcing
	Mineral Extraction	MRD	MJ/kg	Grade decrease
	Non-renewable Energy	FD	MJ/kg	Lower heating value

Table 3: Midpoint categories and Characterization factors

Damage category	Midpoint category			Characterization factor	
	Name	Abb.	Reference substance	Name	Abb.
Human Health	Human Toxicity (Carcinogens + Non-carcinogens)	HT	kg C ₂ H ₃ Cl into air-eq/kg	Human Toxicity Potential	HTP
	Respiratory Effects (inorganics)		kg PM _{2.5} into air-eq/kg		
	Photochemical oxidation (organics)	POF	kg C ₂ H ₄ into air-eq/kg	Photochemical Oxidant Formation Potential	POFP
	Ionizing Radiation	IR	Bq C ₁₄ into air-eq/kg	Ionizing Radiation Potential	IRP
	Ozone layer Depletion	OD	kg CFC-11 into air-eq/kg	Ozone Depletion Potential	ODP
Ecosystem diversity	Aquatic Acidification		kg SO ₂ into air-eq/kg	Acidification Potential	AP
	Aquatic Ecotoxicity	MET	kg TEG into water-eq/kg	Marine Ecotoxicity Potential	METP
	Aquatic Eutrophication	ME	kg PO ₄ ³⁻ into water-eq/kg	Marine Eutrophication Potential	MEP
	Terrestrial acidification/nitrification	TA	kg SO ₂ into air-eq/kg	Terrestrial Acidification Potential	TAP
	Terrestrial Ecotoxicity	TET	kg TEG into soil -eq/kg	Terrestrial Ecotoxicity Potential	TETP
Climate change Resources Availability	Land Occupation	LO	m ² org arable into land-eq· y/m ² ·y	Land Occupation Potential	LOP
	Global Warming	CC	kg CO ₂ into air-eq/kg	Global Warming Potential	GWP
	Mineral Extraction	MRD	MJ surplus energy/kg	Mineral Depletion Potential	MDP
	Non-renewable Energy	FD	MJ surplus energy/kg	Fossil Depletion Potential	FDP

Table 4: Endpoint categories and indicators factors

Endpoint name	Endpoint abb.	Endpoint unit	Indicator
Human Health	HH	DALY	Respiratory effects
Ecosystem Diversity	ED	PDF·m ² ·y	Terrestrial ecotoxicity and land occupation
Climate Change	CC	kg CO ₂ into air-eq	CO ₂ emissions
Resources Availability	RA	MJ	Non-renewable energy consumption

8.1.3 Selection of impact categories

As shown in **Figure 2**, ISO 14044 distinguishes between three mandatory elements (selection, classification, and characterization) and three optional elements (normalization, grouping, and weighing). The optional elements are not always available in all LCA methods.

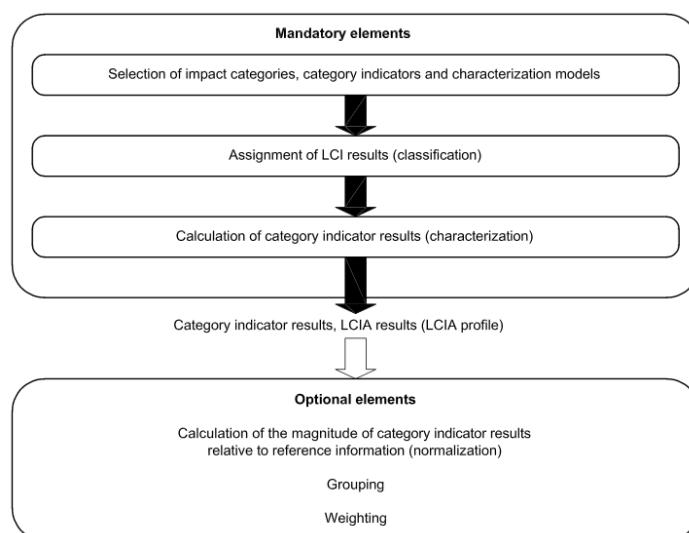


Figure 2: Obligatory and optional elements of LCIA according to ISO 14042

8.1.3.1 Obligatory elements

8.1.3.1.1 Selection of Impact Categories, Category Indicators and Characterization Models (Selection)

The selection of impact categories is the first step within the framework of an impact analysis. However, category indicators connect the LCI emissions and extractions to the impacts through many impact pathways. In practice, impact categories and resulting indicators are structured at two levels: the midpoint level and the endpoint level.

8.1.3.1.2 Assignment of LCI results to the selected impact categories (Classification)

The significant characterization methods are designated and the emission impacts are modelled and represented as impact score in a unit common to all contributions within the impact category. For example, the “kg CO₂-equivalents” unit categorizes the climate change impact category.

8.1.3.1.3 Calculation of category indicator results (Characterization)

The emissions and resource extraction contributing to a certain impact category are multiplied by a characterization factor that expresses the relative contribution of the substance. For example, in the climate change impact category, the characterization factor for CO₂ and methane are equal to 1 and 25 respectively. Thus, releasing 1 kg of methane causes the same amount of climate change as 25kg of CO₂.

In SimaPro, sub-sections could be specified for each substance in order to create a detailed impact assessment method with specific characterization factors. However, some impact assessment methods are not detailed and do not have specific characterization factors. In this case, SimaPro choose the “unspecified” characterization factor as default factor in the chosen impact assessment method.

8.1.3.2 Optional elements

8.1.3.2.1 Normalization

Normalization distinguishes between the impacts categories, expresses the relative magnitude of the impact scores as well as solves the incompatibility of units. After normalization the impact category indicators all have the same unit, which makes it easier to compare them. Normalization (**Equation 1**) can be applied on both characterization and damage assessment results.

For each impact category (k), the normalization values (N) are obtained by dividing the category indicator (N) from characterization by reference values (R). Normalization is determined based on the formula shown below:

Equation1: Normalization formula

$$N_k = \frac{S_k}{R_k}$$

- k = Impact category
- N = Normalization indicator
- S = Category indicator (from characterization)
- R = Reference value

A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. Therefore, the unit of all normalized midpoint/damage factors is [pers*year/unit emission].

8.1.3.2.2 Grouping

The grouping step is an assigning step. It sorts the impact categories to group similar impacts with the possibility of ranking them in order of importance (high, medium, and low priority).

8.1.3.2.3 Weighting

Weighting (**Equation 2**) is a very controversial and challenging step in Life Cycle Impact Assessment, especially for midpoint methods. Upon ISO, weighting is not allowed to be used in public comparative studies. It is used quite extensively for internal decision-making. Weighting is defined in the formula shown below:

Equation 2: Weighting formula

$$EI = \sum V_k N_k \text{ or } EI = \sum V_k S_k$$

- k = Impact category
- EI = Indicator to all environmental impact
- V = Weighting factor
- N = Normalization indicator
- S = Category indicator (from characterization)

The score of the weighting is obtained by the sum of the multiplication of the category indicator (S) with the weighting factor (V). Weighting could be also obtained by the sum of the multiplication of the Normalization indicator (N) with the weighting factor (V). The weighting values are not added to get a single score for comparison purpose with other damage categories because this method is not damage oriented.

The weighting triangle is represented in **Figure 3** and defines the result of an LCA without knowing the weighting factors which will increase the transparency of the weighting process. For instance, the weighting point indicates that the weights of human health, ecosystem quality and resources are 50%, 40% and 10% respectively.

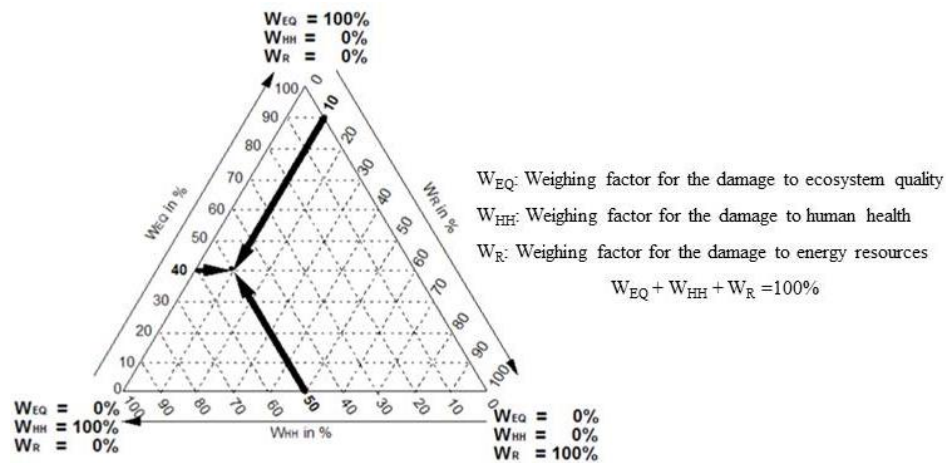


Figure 3: The mixing triangle [Chap1_196]

9 Life Cycle Assessment and Interpretation

The last of the four stages in an LCA study is the Life Cycle Assessment and Interpretation (LCAI) phase. Upon ISO 14044, it is the combination and evaluation of the LCI and LCIA results in order to reach conclusions, limitations and recommendations. This is accomplished by evaluating the sensitivity and uncertainty analyses of significant data elements, assessing the completeness and consistency of the study.

Three analytical procedures were introduced by May et al. to estimate the uncertainty of the Life Cycle Assessment Results:

9.1 Gravity analysis

A gravity analysis or Pareto analysis is also known as 80/20 rule which means that 80% of problems are caused by 20% of the issues or 80% of the revenues come from 20% of the products.

Pareto analysis is a creative statistical procedure for determining data that make the ultimate contribution to the results. This methodology shows the most contributing process to each impact category in the case of a full LCA and the most contributing process to each output in the case of an LCI.

9.2 Uncertainty analysis

In an LCA study, some decisions could be mistaken and inaccurate because the Life Cycle Assessment Results (LCAR) might be affected by some uncertainties. In general, these uncertainties are due to methodological choices, assumptions, system boundaries definition,

and the quality of the available data. For instance, Huijbregts detailed some types of uncertainty:

- Parameter uncertainty: mainly caused by inexact, incomplete, out-of-date, or missed data needed to achieve the inventory analysis.
- Models uncertainty: frequently due to the data collection regarding spatial and temporal features as well as the linear models describing the relationships among environmental phenomena.
- Methodological choices uncertainty: often because of the inevitable methodological choices such as data collection methods, functional unit, system boundaries, etc.
- Spatial variability: this type of uncertainty is correlated to the location and the temporal variability over short and long time scales in LCI and LCIA parameters.

In fact, a particular value might be highly inexact even if its contribution to the uncertainty of the overall result is irrelevant. One of the solutions to determine the uncertainty is a Monte Carlo simulation, which is a “technique that propagates known parameter uncertainties through a calculation to give an uncertainty distribution on the output variables”.

9.3 Sensitivity analysis

The parallel to the uncertainty analysis is the sensitivity analysis. This analysis is an indispensable part of the final interpretation. However, despite it is mentioned in the ISO standards for LCA, there are no guidelines to know how to do or how to select a suitable sensitivity analysis.

A sensitivity analysis identifies which assumptions (modelling of the product system, scope definition, unit processes and data selected...) have the most influence on the result of an LCA study. It aims on the simplification of the data collection and analysis without affecting the quality of the results as well as the identification of the data that must be investigated. Generally, there are three types of sensitivity analysis:

9.3.1 Local sensitivity analysis

1.9.3.1.1 One-at-a-time Approach (OAT)

In this approach, many input parameters are varied at the same time to see how much they will influence the results. In fact, this approach is characterized by its ease to perform and to

understand. However, for large systems it requires lot of time and it could not take into account all parameters systematically; as result it neglect some sensible parameters.

9.3.1.2 Matrix Perturbation (MP)

In 2002, Heijungs and Suh introduce, for the first time, the Matrix perturbation (MP) approach in LCA. MP is based on the conversion of the first order partial derivatives into relative multipliers. With a large multiplier, the variation of the input parameter will affect the result more than if the multiplier is null meaning that the multipliers show the results' direction and magnitude relative to the variation of each factor. Nevertheless, MP is limited to the fact that this methodology considers the actual configuration of a certain model consequently results take only into consideration the small changes of the original parameter.

9.3.2 Screening

9.3.2.1 Method of Elementary Effect (MEE)

Morris designed the Elementary Effects Method (MEE) in 1991, Campolongo et al. developed it in 2007, Koning et al., and Mutel et al. integrated it in LCA in 2010 and 2013 respectively. MEE looks like the updated version of the AOT approach and it considers the range of an individual parameter. This range is the upper and the lower boundaries of an input parameter. For each parameter, MEE is distinguished from AOT by the elementary effect and the calculation of the Standard Deviation (SD) of this effect which is a non-linear indicator. However, this method is limited to the fact the results are not an estimation of the actual variance decomposition.

9.3.3 Global sensitivity analysis or variance based sensitivity analysis

9.3.3.1 Standardized Regression Coefficients (SRC)

One of the approaches that assesses the sensitivity analysis is the Standard Regression Coefficient (SRC). SRC weighs the influence of the errors associated to the estimation of the input variables on the uncertainty of the results and it is calculated from the slope of the line from least square fitting obtained by Monte Carlo simulation (**Equation 3**):

Equation 3: Least square fitting equation

$$y = \beta_0 + \sum_{i=1}^{\delta} \beta_i \cdot X_i$$

y = Output variable
 δ = Uncertainty
 β_i = Linear coefficient
 X_i = Spatial coordinate

For each input parameter, coefficients of regression are intended by standardizing each linear coefficient as represented in **Equation 4**.

Equation 4: Standard regression coefficient equation

$$SRC_i = \frac{\beta_i \cdot \sigma_i}{\sigma_y}$$

β_i = Linear coefficient
 σ_i = Standard deviation
 σ_y = Output variable

A disadvantage of calculating the Standardized Regression Coefficient is the need of many runs to calculate the variance decomposition.

9.3.3.2 Key Issue Analysis (KIA)

In 2002, Heijungs introduced the Key Issue Analysis (KIA) in LCA in order to determine variance decomposition. Heijungs and Huijbregts integrate KIA in LCA in 2004 and Heijungs applied it in 2005. KIA computes the first order of the variance decomposition of individual parameters and does not produce the distribution function. Therefore, it not used for comparing two or more studies.

9.3.3.3 Random Balance Design (RBD)

In 1978, Cukier et al. set the basics of the Random Balance Designs (RBD) but until nowadays, they are not applied in LCA. Even though, Koning et al. applicate, in 2010, a very similar method Fourier amplitude sensitivity test. For each input parameter, Fourier transformations are used by RBD to expect the contribution value to the variance. With RBD, the main effect is only calculated and it is a serious disadvantage for this approach.

9.3.3.4 Sobol' sensitivity index

This sensitivity method calculates, for each input parameter, the allocation of the output variance. It aims on the decomposition of certain model into terms of increasing order and calculates the Sobol' sensitivity index that includes:

- The contribution of variance caused by varying every input parameter to the output variance: Sobol' Main Effect index (SME).
- The contribution of variance caused by varying two or more input parameters simultaneously.
- The contribution of variance caused by the sum of the main and interaction effects of an input parameter: Sobol' Total Effect index (STE).

The calculation of the indices requires many runs hence the Sobol's method is computationally expensive.

In general, the sensitivity methods cited above differ in their input requirements and in the type of results. In addition, optimum operating conditions still unknown and it is unclear if these methods can outdo the standard practices in LCA.

APPENDIX B:
Life cycle inventory for TGBR, WRR, EVR, and IVR

1. Hallow concrete blocks

Every 32 hallow concrete blocks need:

120.00	Kg	of crushed gravel
60.00	Kg	of powder limestone
12.00	Kg	of sand
18.00	Kg	of water
50.00	Kg	of cement



The weight of 32 hallow concrete blocks is 260 Kg
&

The weight of 1 hallow concrete block is 8.13 kg

$$8 \text{ hallow concrete blocks}/1.69\text{m}^2 \Rightarrow \frac{8 \times 834}{1.69} = 3950 \text{ hallow concrete blocks}/834 \text{ m}^2$$

Total weight of hallow concrete blocks : $\frac{3950 \times 8.13}{1000} = 32.09 \text{ tons}$

2. Rebar

50 kg/m³ of concrete

Thickness of roof assembly is 0.27 m

Total roof volume: $835 \times 0.27 = 225.45 \text{ m}^3$

Total weight of rebar: $\frac{50 \times 225.45}{1000} = 11.27 \text{ tons}$

3. Concrete

1m³ of concrete contains:

490.00	Kg	of sand
600.00	Kg	of gravel
175.00	Kg	of water
300.00	Kg	of powder limestone
350.00	Kg	of cement
460.00	Kg	of crushed gravel



The weight of 1m³ of concrete is 2,375 Kg
&

1 ton of concrete is 0.42 m³

Volume of the mockup: $1.3 \times 1.3 \times 0.27 = 0.46 \text{ m}^3$

Volume of 8 hallow concrete blocks: $8 \times [0.4 \times 0.2 \times 0.17] = 0.11 \text{ m}^3$

Volume of rebar is: $[6 \times 3.14 \times (0.006^2) \times 1.2] + [3 \times 3.14 \times (0.007^2) \times 1.2] = 0.001 \text{ m}^3$

Volume of concrete/ $0.46 \text{ m}^3 = \text{Volume of the mockup} - (\text{Volume of 8 hallow concrete blocks} + \text{Volume of rebar})$

$$= 0.46 - (0.11 + .001)$$

$$= 0.34 \text{ m}^3$$

Thickness of the roof assembly is 0.27 m

Total volume of the roof assembly: $835 \times 0.27 = 225.45 \text{ m}^3$

<p>Total volume of concrete: $\frac{0.34 \times 225.45}{0.46} = 170.86 \text{ m}^3$</p>
--

<p>Total weight of concrete: $\frac{170.86 \times 2375}{1000} = 405.79 \text{ tons}$</p>

4. Thermal insulation

67 kg/93 m² for a thickness of 2.5 cm => 268 kg/93 m² for a thickness of 10 cm

<p>Total weight of thermal insulation boards: $\frac{268 \times 834}{93 \times 1000} = 2.40 \text{ tons}$</p>
--

5. Waterproof

Roll weight is $\approx 50 \text{ kg}$

Roll area 9.1 m²

<p>Total weight of waterproof membrane: $\frac{50 \times 834}{9.1 \times 1000} = 4.58 \text{ tons}$</p>
--

6. Filter sheet

Weight of 1m² is 100g

$$\text{Total weight of filter sheet: } \frac{100 \times 834}{1 \times 10^6} = 0.08 \text{ tons}$$

7. Pebbles

Density of pebbles: d= 1853 kg/m³

Thickness of the pebbles layer is 15 cm

Total roof volume: 835 x 0.15 = 125.10 m³

$$\text{Total weight of the pebbles layer : } \frac{125.1 \times 1853}{1000} = 231.80 \text{ tons}$$

8. Reflective membrane

Density of the reflective membrane: d= 4.4 kg/m²

$$\text{Total weight of the reflective membrane : } \frac{4.4 \times 834}{1000} = 3.67 \text{ tons}$$

9. Root barrier

Density of the root barrier for EVR is: d= 330 g/m²

Density of the root barrier for IVR is: d= 1.13 kg/m²

$$\text{Total weight of the root barrier for EVR: } \frac{330 \times 834}{10^6} = 0.28 \text{ ton}$$

$$\text{Total weight of the root barrier for IVR: } \frac{1.13 \times 834}{1000} = 0.94 \text{ ton}$$

10. Drainage

Density of the drainage layer for EVR is: $d = 2 \text{ kg/m}^2$

Density of the drainage layer for IVR is: $d = 2.3 \text{ kg/m}^2$

Total weight of the drainage layer for EVR:	$\frac{2 \times 834}{1000}$	= 1.67 tons
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Total weight of the drainage layer for IVR:	$\frac{2.3 \times 834}{1000}$	= 1.92 tons
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11. Substrate

	For EVR	For IVR
Thickness of the substrate	15 cm	120 cm
Volume of the substrate	$834 \times 0.15 = 125.1 \text{ m}^3$	$834 \times 1.2 = 1000.8 \text{ m}^3$
Sand (55%)	$125.1 \times 55\% = 68.81 \text{ m}^3$	$1000.8 \times 55\% = 550.44 \text{ m}^3$
Fertilizer (10%)	$125.1 \times 10\% = 12.51 \text{ m}^3$	$1000.8 \times 10\% = 100.08 \text{ m}^3$
Pozzolan (17.5%)	$125.1 \times 17.5\% = 21.89 \text{ m}^3$	$1000.8 \times 17.5\% = 175.14 \text{ m}^3$
Perlite (17.5%)	$125.1 \times 17.5\% = 21.89 \text{ m}^3$	$1000.8 \times 17.5\% = 175.14 \text{ m}^3$

Density of sand is: $d = 1602 \text{ kg/m}^3$

Density of fertilizer is: $d = 1 \text{ kg/0.15 m}^3$

Density of pozzolan is: $d = 2150 \text{ kg/m}^3$

Density of perlite is: $d = 1100 \text{ kg/m}^3$

For EVR	Total weight of sand:	$\frac{1602 \times 68.81}{1000}$	= 110.23 tons
	Total weight of fertilizer:	$\frac{12.51 \times 1}{0.15 \times 1000}$	= 0.08 tons
	Total weight of pozzolan:	$\frac{2150 \times 21.89}{1000}$	= 47.06 tons
	Total weight of perlite:	$\frac{1100 \times 21.89}{1000}$	= 24.08 tons

For IVR	Total weight of sand:	$\frac{1602 \times 550.44}{1000}$	= 881.80 tons
	Total weight of fertilizer:	$\frac{100.08 \times 1}{0.15 \times 1000}$	= 0.67 tons
	Total weight of pozzolan:	$\frac{2150 \times 175.14}{1000}$	= 376.55 tons
	Total weight of perlite:	$\frac{1100 \times 175.14}{1000}$	= 192.65 tons

APPENDIX C:
Conversion of weight and distance to “tkm”

	Type	Distance (km)	Weight				tkm			
			TGBR	WRR	EGR	IGR	TGBR	WRR	EGR	IGR
Bricks	Road freight	5.80	32.09				186.12			
	Road freight	19.00	11.27			17.51	214.13			332.69
Steel	Sea freight	13,719.97					154,624.06			240,236.67
	Road freight	4.50					50.72			78.80
Concrete	Road freight	9.00	405.78			453.61	3,652.02			4,082.49
Mastic asphalt	Road freight	5.30	10.01				53.05			
Waterproof membrane	Road freight	604.00		3.34		4.17		2,017.36		2,518.68
	Sea freight	6,082.35								25,363.40
	Road freight	3.90								16.26

	Type	Distance (<i>km</i>)	Weight				tkm			
			TGBR	WRR	EGR	IGR	TGBR	WRR	EGR	IGR
Pozzolan	Sea freight	1,553.40			47.06	322.76			73,103.00	501,375.38
	Road freight	3.90							183.53	1,258.76
Perlite	Sea freight	1,553.40			24.08	165.13			37,405.87	256,512.94
	Road freight	3.90							93.91	644.01
Pebbles	Road freight	118.00	231.81				27,353.58	0.00		
Reflective membrane	Road freight	398.00		3.50				1,393.00		
	Sea freight	6,569.48						22,993.18		
	Road freight	3.90						13.65		

APPENDIX D:

Amount of material needed for TGBR, EVR8, and EVR16 mockups

1. Hallow concrete blocks

Every 32 hallow concrete blocks need:

120.00	Kg	of crushed gravel
60.00	Kg	of powder limestone
12.00	Kg	of sand
18.00	Kg	of water
50.00	Kg	of cement



The weight of 32 hallow concrete blocks is 260 Kg

&

The weight of 1 hallow concrete block is 8.13 kg

Area of the mockup is: $0.7 \times 0.7 = 0.49 \text{ m}^2$

8 hallow concrete blocks/ $1.69 \text{ m}^2 \Rightarrow \frac{8 \times 0.49}{1.69} = 2$ hallow concrete blocks/ 0.49 m^2

Total weight of hallow concrete blocks : $\frac{2 \times 8.13}{1000} = 16.25 \text{ kg}$
--

2. Rebar

50 kg/ m^3 of concrete

Thickness of roof assembly is 0.27 m

Total roof volume: $0.49 \times 0.27 = 0.13 \text{ m}^3$

Total weight of rebar: $\frac{50 \times 0.13}{1} = 6.5 \text{ kg}$
--

3. Concrete

1 m^3 of concrete contains:

490.00	Kg	of sand
600.00	Kg	of gravel
175.00	Kg	of water
300.00	Kg	of powder limestone
350.00	Kg	of cement
460.00	Kg	of crushed gravel



The weight of 1 m^3 of concrete is 2,375 Kg

&

1 ton of concrete is 0.42 m^3

Volume of the mockup: $1.3 \times 1.3 \times 0.27 = 0.46 \text{ m}^3$

Volume of 8 hallow concrete blocks: $8 \times [0.4 \times 0.2 \times 0.17] = 0.11 \text{ m}^3$

Volume of rebar is: $[6 \times 3.14 \times (0.006^2) \times 1.2] + [3 \times 3.14 \times (0.007^2) \times 1.2] = 0.001 \text{ m}^3$

Volume of concrete/ $0.46 \text{ m}^3 = \text{Volume of the mockup} - (\text{Volume of 8 hallow concrete blocks} + \text{Volume of rebar})$

$$= 0.46 - (0.11 + .001)$$

$$= 0.34 \text{ m}^3$$

Thickness of the roof assembly is 0.27 m

Total volume of the roof assembly: $0.49 \times 0.27 = 0.13 \text{ m}^3$

Total volume of concrete: $\frac{0.34 \times 0.13}{0.46} = 0.10 \text{ m}^3$
--

Total weight of concrete: $\frac{0.10 \times 2375}{1000} = 0.24 \text{ tons}$

4. Thermal insulation

67 kg/93 m² for a thickness of 2.5 cm => 107.2 kg/93 m² for a thickness of 4 cm

Total weight of thermal insulation boards: $\frac{107.2 \times 0.49}{93} = 0.56 \text{ kg}$

5. Waterproof

Roll weight is $\approx 50 \text{ kg}$

Roll area 9.1 m²

Total weight of waterproof membrane: $\frac{50 \times 0.49}{9.1} = 2.69 \text{ kg}$

6. Filter sheet

Weight of 1m² is 100g

Total weight of filter sheet: $\frac{100 \times 0.49}{1000} = 0.05 \text{ kg}$
--

7. Pebbles

Density of pebbles: d= 1853 kg/m³

Thickness of the pebbles layer is 10 cm

Total roof volume: 0.49 x 0.1 = 0.049 m³

Total weight of the pebbles layer : $\frac{0.049 \times 1853}{1} = 90.80 \text{ kg}$
--

8. Root barrier

Density of the root barrier is: d= 330 g/m²

Total weight of the root barrier for EVR: $\frac{330 \times 0.49}{1000} = 0.16 \text{ kg}$
--

9. Drainage

Density of the drainage layer is: d= 2 kg/m²

Total weight of the drainage layer for EVR: $\frac{2 \times 0.49}{1} = 0.98 \text{ kg}$

10. Substrate

	For EVR8	For EVR16
Thickness of the substrate	8.000 cm	16.000 cm
Volume of the substrate	$0.49 \times 0.08 = 0.039 \text{ m}^3$	$0.49 \times 0.16 = 0.078 \text{ m}^3$
Soil (20%)	$0.039 \times 20\% = 0.007 \text{ m}^3$	$0.078 \times 20\% = 0.016 \text{ m}^3$
Peat (33%)	$0.039 \times 33\% = 0.013 \text{ m}^3$	$0.078 \times 33\% = 0.025 \text{ m}^3$
Pumice (20% for EVR8 & 40% EVR16)	$0.039 \times 20\% = 0.008 \text{ m}^3$	$0.078 \times 40\% = 0.031 \text{ m}^3$
Alumina (20% for EVR8 & 0% EVR16)	$0.039 \times 20\% = 0.008 \text{ m}^3$	$0.078 \times 0\% = 0.000 \text{ m}^3$
Fertilizer (7%)	$0.039 \times 7\% = 0.003 \text{ m}^3$	$0.039 \times 7\% = 0.006 \text{ m}^3$

Density of soil is: $d = 1600 \text{ kg/m}^3$

Density of peat is: $d = 1650 \text{ kg/m}^3$

Density of alumina is: $d = 3690 \text{ kg/m}^3$

Density of pumice is: $d = 641 \text{ kg/m}^3$

Density of fertilizer is: $d = 1 \text{ kg}/0.15 \text{ m}^3$

Total weight of soil: $1600 \times 0.007 = 11.2 \text{ kg}$	
Total weight of peat: $1650 \times 0.013 = 21.45 \text{ kg}$	
EVR8:	Total weight of alumina: $3690 \times 0.008 = 28.80 \text{ kg}$
Total weight of pumice: $641 \times 0.008 = 5.13 \text{ kg}$	
Total weight of fertilizer: $0.003 \div 0.15 = 0.02 \text{ kg}$	

Total weight of soil: $1600 \times 0.016 = 25.6 \text{ kg}$	
Total weight of peat: $1650 \times 0.025 = 41.25 \text{ kg}$	
EVR16:	Total weight of alumina: $3690 \times 0 = 0 \text{ kg}$
Total weight of pumice: $641 \times 0.031 = 19.87 \text{ kg}$	
Total weight of fertilizer: $0.006 \div 0.15 = 0.04 \text{ kg}$	

APPENDIX E:
HDD for January, February, and March 2016

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0
Jan 1, 2016	6.30	5.20	4.00	-11.70	-12.80	-14.00	11.70	12.80	14.00
Jan 2, 2016	3.21	2.21	2.46	-14.79	-15.79	-15.54	14.79	15.79	15.54
Jan 3, 2016	4.91	4.39	5.08	-13.09	-13.61	-12.92	13.09	13.61	12.92
Jan 4, 2016	6.42	5.69	6.29	-11.58	-12.31	-11.71	11.58	12.31	11.71
Jan 5, 2016	10.55	10.05	10.54	-7.45	-7.95	-7.46	7.45	7.95	7.46
Jan 6, 2016	11.91	11.23	11.85	-6.09	-6.77	-6.15	6.09	6.77	6.15
Jan 7, 2016	12.58	11.51	12.27	-5.42	-6.49	-5.73	5.42	6.49	5.73
Jan 8, 2016	10.59	10.83	9.72	-7.41	-7.17	-8.28	7.41	7.17	8.28
Jan 9, 2016	9.54	10.99	8.87	-8.46	-7.01	-9.13	8.46	7.01	9.13
Jan 10, 2016	8.97	11.20	8.73	-9.03	-6.80	-9.27	9.03	6.80	9.27
Jan 11, 2016	10.40	12.04	10.72	-7.60	-5.96	-7.28	7.60	5.96	7.28
Jan 12, 2016	11.28	12.37	10.84	-6.72	-5.63	-7.16	6.72	5.63	7.16
Jan 13, 2016	11.49	13.18	11.69	-6.51	-4.82	-6.31	6.51	4.82	6.31
Jan 14, 2016	11.72	12.81	11.49	-6.28	-5.19	-6.51	6.28	5.19	6.51
Jan 15, 2016	12.12	12.89	11.91	-5.88	-5.11	-6.09	5.88	5.11	6.09
Jan 16, 2016	11.57	13.05	11.12	-6.43	-4.95	-6.88	6.43	4.95	6.88
Jan 17, 2016	11.99	16.05	13.92	-6.01	-1.95	-4.08	6.01	1.95	4.08
Jan 18, 2016	11.62	11.66	11.81	-6.38	-6.34	-6.19	6.38	6.34	6.19
Jan 19, 2016	8.20	8.65	7.22	-9.80	-9.35	-10.78	9.80	9.35	10.78
Jan 20, 2016	8.04	9.07	7.39	-9.96	-8.93	-10.61	9.96	8.93	10.61
Jan 21, 2016	8.54	11.31	7.76	-9.46	-6.69	-10.24	9.46	6.69	10.24
Jan 22, 2016	10.02	12.65	9.97	-7.98	-5.35	-8.03	7.98	5.35	8.03
Jan 23, 2016	10.67	9.73	9.66	-7.33	-8.27	-8.34	7.33	8.27	8.34

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0
Jan 24, 2016	7.91	6.26	6.11	-10.09	-11.74	-11.89	10.09	11.74	11.89
Jan 25, 2016	4.72	4.31	2.86	-13.28	-13.69	-15.14	13.28	13.69	15.14
Jan 26, 2016	3.48	2.04	1.61	-14.52	-15.96	-16.39	14.52	15.96	16.39
Jan 27, 2016	2.51	1.75	1.69	-15.49	-16.25	-16.31	15.49	16.25	16.31
Jan 28, 2016	2.49	1.81	2.56	-15.51	-16.19	-15.44	15.51	16.19	15.44
Jan 29, 2016	5.65	5.57	8.12	-12.35	-12.43	-9.88	12.35	12.43	9.88
Jan 30, 2016	9.04	9.12	10.21	-8.96	-8.88	-7.79	8.96	8.88	7.79
Jan 31, 2016	10.64	10.53	11.34	-7.36	-7.47	-6.66	7.36	7.47	6.66

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Feb 1, 2016	11.53	10.95	12.03	-6.47	-7.05	-5.97	6.47	7.05	5.97
Feb 2, 2016	11.79	10.87	12.28	-6.21	-7.13	-5.72	6.21	7.13	5.72
Feb 3, 2016	12.04	11.35	12.93	-5.96	-6.65	-5.07	5.96	6.65	5.07
Feb 4, 2016	12.91	12.17	14.39	-5.09	-5.83	-3.61	5.09	5.83	3.61
Feb 5, 2016	14.39	13.61	16.71	-3.61	-4.39	-1.29	3.61	4.39	1.29
Feb 6, 2016	12.27	12.58	11.22	-5.73	-5.42	-6.78	5.73	5.42	6.78
Feb 7, 2016	8.61	8.13	7.44	-9.39	-9.87	-10.56	9.39	9.87	10.56
Feb 8, 2016	8.65	8.33	7.88	-9.35	-9.67	-10.12	9.35	9.67	10.12
Feb 9, 2016	9.22	8.81	8.86	-8.78	-9.19	-9.14	8.78	9.19	9.14

Date	AVERAGE			Date	T-T _{base}			HDD	
	EGR16_th	EGR8_th	TGBR_th		EGR16_th	EGR8_th	TGBR_th	Date	EGR16_th
Feb 10, 2016	10.11	9.54	9.82	-7.89	-8.46	-8.18	7.89	8.46	8.18
Feb 11, 2016	11.02	10.19	10.83	-6.98	-7.81	-7.17	6.98	7.81	7.17
Feb 12, 2016	11.74	11.51	12.47	-6.26	-6.49	-5.53	6.26	6.49	5.53
Feb 13, 2016	13.53	13.26	14.27	-4.47	-4.74	-3.73	4.47	4.74	3.73
Feb 14, 2016	14.70	14.08	15.26	-3.30	-3.92	-2.74	3.30	3.92	2.74
Feb 15, 2016	16.02	14.91	17.06	-1.98	-3.09	-0.94	1.98	3.09	0.94
Feb 16, 2016	17.11	15.63	18.31	-0.89	-2.37	0.31	0.89	2.37	0.00
Feb 17, 2016	18.19	17.52	20.11	0.19	-0.48	2.11	0.00	0.48	0.00
Feb 18, 2016	19.64	18.94	20.90	1.64	0.94	2.90	0.00	0.00	0.00
Feb 19, 2016	18.99	18.71	20.54	0.99	0.71	2.54	0.00	0.00	0.00
Feb 20, 2016	15.57	16.61	16.30	-2.43	-1.39	-1.70	2.43	1.39	1.70
Feb 21, 2016	14.36	14.43	13.86	-3.64	-3.57	-4.14	3.64	3.57	4.14
Feb 22, 2016	12.68	12.11	10.92	-5.32	-5.89	-7.08	5.32	5.89	7.08
Feb 23, 2016	13.06	12.67	12.26	-4.94	-5.33	-5.74	4.94	5.33	5.74
Feb 24, 2016	13.89	13.66	13.22	-4.11	-4.34	-4.78	4.11	4.34	4.78
Feb 25, 2016	14.94	14.79	14.20	-3.06	-3.21	-3.80	3.06	3.21	3.80
Feb 26, 2016	17.34	17.27	17.69	-0.66	-0.73	-0.31	0.66	0.73	0.31
Feb 27, 2016	19.06	19.01	19.40	1.06	1.01	1.40	0.00	0.00	0.00
Feb 28, 2016	17.85	17.66	17.19	-0.15	-0.34	-0.81	0.15	0.34	0.81
Feb 29, 2016	18.52	18.45	19.65	0.52	0.45	1.65	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Mar 1, 2016	20.66	20.27	22.30	2.66	2.27	4.30	0.00	0.00	0.00
Mar 2, 2016	21.70	21.29	23.43	3.70	3.29	5.43	0.00	0.00	0.00
Mar 3, 2016	19.41	19.01	19.31	1.41	1.01	1.31	0.00	0.00	0.00
Mar 4, 2016	15.08	14.83	15.17	-2.92	-3.17	-2.83	2.92	3.17	2.83
Mar 5, 2016	14.97	15.20	16.06	-3.03	-2.80	-1.94	3.03	2.80	1.94
Mar 6, 2016	14.64	15.01	15.15	-3.36	-2.99	-2.85	3.36	2.99	2.85
Mar 7, 2016	15.58	15.37	16.62	-2.42	-2.63	-1.38	2.42	2.63	1.38
Mar 8, 2016	18.87	18.00	21.55	0.87	0.00	3.55	0.00	0.00	0.00
Mar 9, 2016	20.81	19.94	22.41	2.81	1.94	4.41	0.00	0.00	0.00
Mar 10, 2016	19.66	19.35	20.25	1.66	1.35	2.25	0.00	0.00	0.00
Mar 11, 2016	17.05	16.51	16.55	-0.95	-1.49	-1.45	0.95	1.49	1.45
Mar 12, 2016	16.25	15.70	16.23	-1.75	-2.31	-1.77	1.75	2.31	1.77
Mar 13, 2016	18.14	18.25	19.77	0.14	0.25	1.77	0.00	0.00	0.00
Mar 14, 2016	19.29	18.72	18.58	1.29	0.72	0.58	0.00	0.00	0.00
Mar 15, 2016	13.62	13.04	12.15	-4.38	-4.96	-5.85	4.38	4.96	5.85
Mar 16, 2016	12.09	12.03	11.34	-5.91	-5.97	-6.66	5.91	5.97	6.66
Mar 17, 2016	12.55	12.59	11.98	-5.45	-5.41	-6.02	5.45	5.41	6.02
Mar 18, 2016	13.45	13.04	12.75	-4.55	-4.96	-5.25	4.55	4.96	5.25
Mar 19, 2016	14.52	14.02	14.03	-3.48	-3.98	-3.97	3.48	3.98	3.97
Mar 20, 2016	15.68	15.06	15.60	-2.32	-2.94	-2.40	2.32	2.94	2.40
Mar 21, 2016	14.16	13.65	13.24	-3.84	-4.35	-4.76	3.84	4.35	4.76
Mar 22, 2016	14.75	14.50	14.31	-3.25	-3.50	-3.69	3.25	3.50	3.69
Mar 23, 2016	16.33	16.02	16.38	-1.67	-1.98	-1.62	1.67	1.98	1.62

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Mar 24, 2016	19.83	19.97	22.03	1.83	1.97	4.03	0.00	0.00	0.00
Mar 25, 2016	19.50	19.25	20.02	1.50	1.25	2.02	0.00	0.00	0.00
Mar 26, 2016	17.48	16.64	17.32	-0.52	-1.36	-0.68	0.52	1.36	0.68
Mar 27, 2016	15.92	15.15	14.93	-2.08	-2.85	-3.07	2.08	2.85	3.07
Mar 28, 2016	12.87	11.79	10.92	-5.13	-6.21	-7.08	5.13	6.21	7.08
Mar 29, 2016	12.20	12.21	11.92	-5.80	-5.79	-6.08	5.80	5.79	6.08
Mar 30, 2016	14.28	13.90	13.90	-3.72	-4.10	-4.10	3.72	4.10	4.10
Mar 31, 2016	15.59	15.29	14.73	-2.41	-2.71	-3.27	2.41	2.71	3.27

APPENDIX F:
CDD for January, February, and March 2016

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0
Jan 1, 2016	6.30	5.20	4.00	14.70	15.80	17.00	0.00	0.00	0.00
Jan 2, 2016	3.21	2.21	2.46	17.79	18.79	18.54	0.00	0.00	0.00
Jan 3, 2016	4.91	4.39	5.08	16.09	16.61	15.92	0.00	0.00	0.00
Jan 4, 2016	6.42	5.69	6.29	14.58	15.31	14.71	0.00	0.00	0.00
Jan 5, 2016	10.55	10.05	10.54	10.45	10.95	10.46	0.00	0.00	0.00
Jan 6, 2016	11.91	11.23	11.85	9.09	9.77	9.15	0.00	0.00	0.00
Jan 7, 2016	12.58	11.51	12.27	8.42	9.49	8.73	0.00	0.00	0.00
Jan 8, 2016	10.59	10.83	9.72	10.41	10.17	11.28	0.00	0.00	0.00
Jan 9, 2016	9.54	10.99	8.87	11.46	10.01	12.13	0.00	0.00	0.00
Jan 10, 2016	8.97	11.20	8.73	12.03	9.80	12.27	0.00	0.00	0.00
Jan 11, 2016	10.40	12.04	10.72	10.60	8.96	10.28	0.00	0.00	0.00
Jan 12, 2016	11.28	12.37	10.84	9.72	8.63	10.16	0.00	0.00	0.00
Jan 13, 2016	11.49	13.18	11.69	9.51	7.82	9.31	0.00	0.00	0.00
Jan 14, 2016	11.72	12.81	11.49	9.28	8.19	9.51	0.00	0.00	0.00
Jan 15, 2016	12.12	12.89	11.91	8.88	8.11	9.09	0.00	0.00	0.00
Jan 16, 2016	11.57	13.05	11.12	9.43	7.95	9.88	0.00	0.00	0.00
Jan 17, 2016	11.99	16.05	13.92	9.01	4.95	7.08	0.00	0.00	0.00
Jan 18, 2016	11.62	11.66	11.81	9.38	9.34	9.19	0.00	0.00	0.00
Jan 19, 2016	8.20	8.65	7.22	12.80	12.35	13.78	0.00	0.00	0.00
Jan 20, 2016	8.04	9.07	7.39	12.96	11.93	13.61	0.00	0.00	0.00
Jan 21, 2016	8.54	11.31	7.76	12.46	9.69	13.24	0.00	0.00	0.00
Jan 22, 2016	10.02	12.65	9.97	10.98	8.35	11.03	0.00	0.00	0.00
Jan 23, 2016	10.67	9.73	9.66	10.33	11.27	11.34	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0	EGR16_th	EGR8_th	TGBR_0
Jan 24, 2016	7.91	6.26	6.11	13.09	14.74	14.89	0.00	0.00	0.00
Jan 25, 2016	4.72	4.31	2.86	16.28	16.69	18.14	0.00	0.00	0.00
Jan 26, 2016	3.48	2.04	1.61	17.52	18.96	19.39	0.00	0.00	0.00
Jan 27, 2016	2.51	1.75	1.69	18.49	19.25	19.31	0.00	0.00	0.00
Jan 28, 2016	2.49	1.81	2.56	18.51	19.19	18.44	0.00	0.00	0.00
Jan 29, 2016	5.65	5.57	8.12	15.35	15.43	12.88	0.00	0.00	0.00
Jan 30, 2016	9.04	9.12	10.21	11.96	11.88	10.79	0.00	0.00	0.00
Jan 31, 2016	10.64	10.53	11.34	10.36	10.47	9.66	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Feb 1, 2016	11.53	10.95	12.03	9.47	10.05	8.97	0.00	0.00	0.00
Feb 2, 2016	11.79	10.87	12.28	9.21	10.13	8.72	0.00	0.00	0.00
Feb 3, 2016	12.04	11.35	12.93	8.96	9.65	8.07	0.00	0.00	0.00
Feb 4, 2016	12.91	12.17	14.39	8.09	8.83	6.61	0.00	0.00	0.00
Feb 5, 2016	14.39	13.61	16.71	6.61	7.39	4.29	0.00	0.00	0.00
Feb 6, 2016	12.27	12.58	11.22	8.73	8.42	9.78	0.00	0.00	0.00
Feb 7, 2016	8.61	8.13	7.44	12.39	12.87	13.56	0.00	0.00	0.00
Feb 8, 2016	8.65	8.33	7.88	12.35	12.67	13.12	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Feb 9, 2016	9.22	8.81	8.86	11.78	12.19	12.14	0.00	0.00	0.00
Feb 10, 2016	10.11	9.54	9.82	10.89	11.46	11.18	0.00	0.00	0.00
Feb 11, 2016	11.02	10.19	10.83	9.98	10.81	10.17	0.00	0.00	0.00
Feb 12, 2016	11.74	11.51	12.47	9.26	9.49	8.53	0.00	0.00	0.00
Feb 13, 2016	13.53	13.26	14.27	7.47	7.74	6.73	0.00	0.00	0.00
Feb 14, 2016	14.70	14.08	15.26	6.30	6.92	5.74	0.00	0.00	0.00
Feb 15, 2016	16.02	14.91	17.06	4.98	6.09	3.94	0.00	0.00	0.00
Feb 16, 2016	17.11	15.63	18.31	3.89	5.37	2.69	0.00	0.00	0.00
Feb 17, 2016	18.19	17.52	20.11	2.81	3.48	0.89	0.00	0.00	0.00
Feb 18, 2016	19.64	18.94	20.90	1.36	2.06	0.10	0.00	0.00	0.00
Feb 19, 2016	18.99	18.71	20.54	2.01	2.29	0.46	0.00	0.00	0.00
Feb 20, 2016	15.57	16.61	16.30	5.43	4.39	4.70	0.00	0.00	0.00
Feb 21, 2016	14.36	14.43	13.86	6.64	6.57	7.14	0.00	0.00	0.00
Feb 22, 2016	12.68	12.11	10.92	8.32	8.89	10.08	0.00	0.00	0.00
Feb 23, 2016	13.06	12.67	12.26	7.94	8.33	8.74	0.00	0.00	0.00
Feb 24, 2016	13.89	13.66	13.22	7.11	7.34	7.78	0.00	0.00	0.00
Feb 25, 2016	14.94	14.79	14.20	6.06	6.21	6.80	0.00	0.00	0.00
Feb 26, 2016	17.34	17.27	17.69	3.66	3.73	3.31	0.00	0.00	0.00
Feb 27, 2016	19.06	19.01	19.40	1.94	1.99	1.60	0.00	0.00	0.00
Feb 28, 2016	17.85	17.66	17.19	3.15	3.34	3.81	0.00	0.00	0.00
Feb 29, 2016	18.52	18.45	19.65	2.48	2.55	1.35	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Mar 1, 2016	20.66	20.27	22.30	0.34	0.73	-1.30	0.00	0.00	1.30
Mar 2, 2016	21.70	21.29	23.43	-0.70	-0.29	-2.43	0.70	0.29	2.43
Mar 3, 2016	19.41	19.01	19.31	1.59	1.99	1.69	0.00	0.00	0.00
Mar 4, 2016	15.08	14.83	15.17	5.92	6.17	5.83	0.00	0.00	0.00
Mar 5, 2016	14.97	15.20	16.06	6.03	5.80	4.94	0.00	0.00	0.00
Mar 6, 2016	14.64	15.01	15.15	6.36	5.99	5.85	0.00	0.00	0.00
Mar 7, 2016	15.58	15.37	16.62	5.42	5.63	4.38	0.00	0.00	0.00
Mar 8, 2016	18.87	18.00	21.55	2.13	3.00	-0.55	0.00	0.00	0.55
Mar 9, 2016	20.81	19.94	22.41	0.19	1.06	-1.41	0.00	0.00	1.41
Mar 10, 2016	19.66	19.35	20.25	1.34	1.65	0.75	0.00	0.00	0.00
Mar 11, 2016	17.05	16.51	16.55	3.95	4.49	4.45	0.00	0.00	0.00
Mar 12, 2016	16.25	15.70	16.23	4.75	5.31	4.77	0.00	0.00	0.00
Mar 13, 2016	18.14	18.25	19.77	2.86	2.75	1.23	0.00	0.00	0.00
Mar 14, 2016	19.29	18.72	18.58	1.71	2.28	2.42	0.00	0.00	0.00
Mar 15, 2016	13.62	13.04	12.15	7.38	7.96	8.85	0.00	0.00	0.00
Mar 16, 2016	12.09	12.03	11.34	8.91	8.97	9.66	0.00	0.00	0.00
Mar 17, 2016	12.55	12.59	11.98	8.45	8.41	9.02	0.00	0.00	0.00
Mar 18, 2016	13.45	13.04	12.75	7.55	7.96	8.25	0.00	0.00	0.00
Mar 19, 2016	14.52	14.02	14.03	6.48	6.98	6.97	0.00	0.00	0.00
Mar 20, 2016	15.68	15.06	15.60	5.32	5.94	5.40	0.00	0.00	0.00
Mar 21, 2016	14.16	13.65	13.24	6.84	7.35	7.76	0.00	0.00	0.00
Mar 22, 2016	14.75	14.50	14.31	6.25	6.50	6.69	0.00	0.00	0.00
Mar 23, 2016	16.33	16.02	16.38	4.67	4.98	4.62	0.00	0.00	0.00

Date	AVERAGE			T-T _{base}			HDD		
	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th	EGR16_th	EGR8_th	TGBR_th
Mar 24, 2016	19.83	19.97	22.03	1.17	1.03	-1.03	0.00	0.00	1.03
Mar 25, 2016	19.50	19.25	20.02	1.50	1.75	0.98	0.00	0.00	0.00
Mar 26, 2016	17.48	16.64	17.32	3.52	4.36	3.68	0.00	0.00	0.00
Mar 27, 2016	15.92	15.15	14.93	5.08	5.85	6.07	0.00	0.00	0.00
Mar 28, 2016	12.87	11.79	10.92	8.13	9.21	10.08	0.00	0.00	0.00
Mar 29, 2016	12.20	12.21	11.92	8.80	8.79	9.08	0.00	0.00	0.00
Mar 30, 2016	14.28	13.90	13.90	6.72	7.10	7.10	0.00	0.00	0.00
Mar 31, 2016	15.59	15.29	14.73	5.41	5.71	6.27	0.00	0.00	0.00